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RELIABILITY PREDICTION, ASSESSMENT AND GROWTH

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March 15, 1976

Final Report

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RELIABILITY PREDICTION, ASSESSMENT AND GROWTH

IITRI E6304

Kent J. Kogler

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FOREWORD

This document is the final report on IIT Research Institute Project E6304; "Reliability Prediction, Assessment and Growth," covering work performed during the period July 1974 to September 1975. This effort was performed for the U.S. Army, Aviation Systems Command (AVSCOM) Product Assurance Director, R&M Division under Contract No. DAAJ01-74-C-0653 (P1G).

This report provides a detailed methodology which represents an improved method to evaluate the reliability aspects of product improvement proposals, to determine the relationship between inherent and operational reliability, to establish the initial reliability of newly developed helicopter systems and to control and grow reliability during production.

Incorporated in the report is a detailed procedure outlining the application of the methodology to assess and control post production reliability growth. Implementation of the procedure is supported by a gross data base compiled during the study and the presentation of a detailed plan for the development of a helicopter reliability data repository and analysis center.

During the period of work, monthly progress reports have been submitted to AVSCOM. In addition, draft results have been presented at formal (review) meetings at IITRI (May 2, 1975; June 5, 1975) and at AVSCOM (September 18, 1975). This final report includes all information submitted in previous reports and incorporates all government comments from the review of the draft documents presented at the review meetings.

At IITRI, this project was conducted under the direction of R.T. Anderson, Manager, Reliability Section. The project manager was Kent Kogler. Technical contributors to the report were D. Kos, L. Townsend, J. Schiller, N. Thomopoulos and V. Allen.

On the part of the government, the project was under the technical cognizance of Mr. Lewis Neri, Cheif of Reliability and Maintainability Division, Directorate for Product Assurance, U.S. Army, Aviation Systems Command. During the course of this effort, Mr. Elmer Lueckerath has provided valuable assistance in the arrangement of meetings and collection of data from both Army and prime helicopter contractors. This information contributed significantly to the success of the program.

TABLE OF CONTENTS

TABLE OF CONTENTS (Cont'd)

LIST OF TABLES

LIST OF FIGURES

LIST OF FIGURES (Cont'd)

1.0 INTRODUCTION

Complex, modern day aviation systems such as Army helicopters require much more than sophisticated performance and versatility. Such systems demand high levels of field reliability to render their operation both safe and cost effective. To meet this need, a total life cycle reliability program is required -- one that does not stop after design and development but continues through production as well as during field use. Only through a total life cycle program that is executed by well disciplined engineering methods and procedures, can safe, reliable, economical helicopter systems be achieved.

The basic framework for developing the detailed techniques and procedures to implement this philosophy is defined in AVSCOM's R&M management guidebook.[1] The entire range of reliability engineering efforts as they relate to all phases of a helicopter's life cycle are covered in the guidebook. This report addresses the production phase, which historically is the portion of a helicopter's life cycle that accounts for much of its unreliability, and which traditionally has had no detailed engineering reliability procedures. It provides a detailed methodology for assessing the overall reliability of a helicopter system or component as it leaves production, by taking into account production degradation factors due to manufacturing process, induced defects and imperfect inspection.

The methodology represents an improved method to evaluate quantitatively the reliability impact of design and process changes and in particular to determine more fully the reliability impact of implementing product improvement proposals for fielded systems. Furthermore, the methodology provides a means to determine the relationship between inherent (design-based) and operational (as released from production) MTBF. Also the methodology can be used to establish the initial MTBF of newly developed helicopter systems (and/or components) as they are released for operational use.

Specifically this report provides a detailed step by step procedure to:

1. Evaluate the magnitude of defects induced by a manufacturing process
2. Estimate the efficiency of manufacturing inspections
3. Compute the reliability of systems and components leaving production.

In addition, a preliminary data base is provided containing gross defect rates and inspection efficiency factors as collected from on sight visits to helicopter manufacturers; interviews with contractors, subcontractors and Army personnel, and collection and review of historical data. This data can be used in conjunction with the step by step procedure, to evaluate post production reliability. Several examples are given to validate the methodology, illustrate how the technique is used and to demonstrate how iteration of the methodology, as production processes and inspection efficiencies are improved, allows assessment and control of reliability growth.

1.1 Background

The foundations for this investigation become evident when considering that (a) manufacturing operations introduce unreliability into hardware that is not ordinarily accounted for by inherent reliability (design) predictions, and (b) inspection and test procedures normally interleaved in fabrication processes are imperfect and allow defects to escape which later result in field failures.

Since manufacturing defects and flaws cannot be eliminated solely though design and development action prior to the buildup of production hardware, a design-based reliability estimate in itself is not useful for accurately assessing actual use reliability. To realistically estimate reliability, the degradation factors resulting from manufacturing and the operating and maintenance environment must be taken into account. These degradation factors must be assessed and quantified in order to accurately estimate and control reliability. Production degradation is a particularly important factor when considering newly fabricated hardware items, where manufacturing learning is not yet complete and a high initial defect and error rate can be expected.

This high initial defect rate is defined as the infant mortality period of a system and/or component item's life characteristic curve (bathtub curve). In general, the infant mortality period (as well as all periods of the operating life characteristic curve) is comprised of three (3) separate failure components. Figure 1-1 illustrates these failure components as they relate to the hardware operating life periods, in terms of rate of failure (λ).

The failure components are:

1. Quality failures - due to design and quality-related manufacturing defects and/or flaws and have a decreasing failure rate.

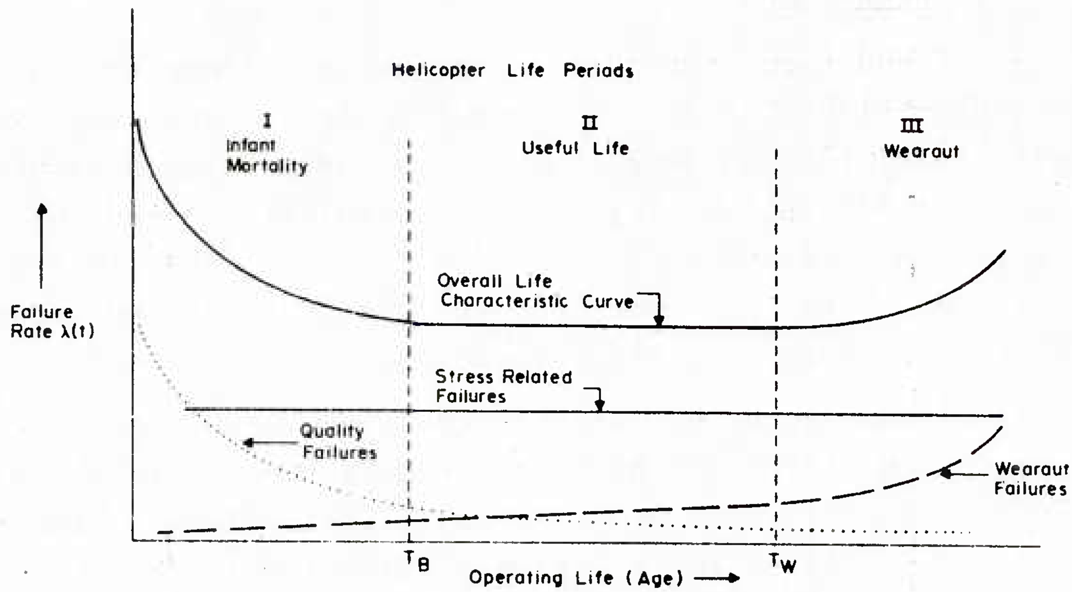


Figure 1-1 COMPONENTS OF FAILURE

2. Stress Related Failure - due to application stresses and which have a constant failure rate.

3. Wearout Failure - due to aging and/or deterioration and which have an increasing failure rate.

Examination of Figure 1-1 indicates that the infant mortality period is characterized by a high but rapidly decreasing failure rate that is comprised of a high quality failure component, a constant stress related failure component, and a low wearout failure component. The figure shows that the useful life period is characterized by a constant failure rate that is comprised of a low and (decreasing) quality failure component, a constant stress related failure component, and a low (but increasing) wearout failure component. Note that the combination of all three components during the useful life period result in a constant failure rate because the decreasing quality failures and increasing wearout failures tend to off-set each other, and because the stress related failures exhibit a relatively large amplitude. The wearout period, as shown in Figure 1-1 is characterized by an increasing failure rate that is comprised of a negligible quality failure component, a constant stress related failure component, and an initially low, but rapidly increasing, wearout failure component.

Total reliability effort involves control of these failure rates during all hardware life cycle periods. The treditional approach to reliability is to minimize early failures by emphasizing factory test and inspection and preventing wear-out failures by replacing short life parts. Consequently, the useful life period characterized by stress related failures has been the most important period, and the one to which design action is primarily addressed. Reliability prediction efforts, usually address the useful life period and resulting predictions reflect the inherent reliability of an item as determined from

- stress and strength factors (derating)
- application environment
- manufacturing and quality factors

Stress related failures are evaluated through probabilistic design analysis and are minimized by incorporating adequate design margins. Figure 1-2 shows the interaction of stress and strength relative to the useful life period identified in Figure 1-1.

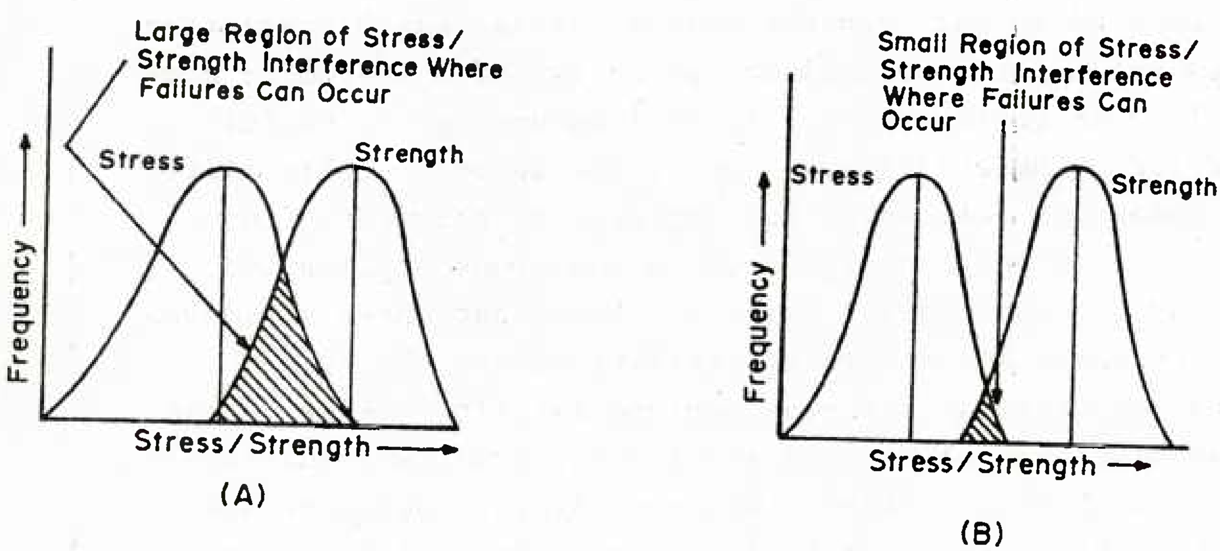


Figure 1-2 STRESS VERSUS STRENGTH DISTRIBUTIONS

Figure 1-2 (A) illustrates the distribution of a typical stress/strength density curve for an item having low reliability and/or inadequate design margin. The shaded area indicates that stress exceeds strength a certain percentage of time, with resultant failure. In contrast, Figure 1-2 (B) shows the separation of the stress/strength distribution indicative of a high design safety factor (adequate design margin) and high reliability.

It must be stressed that the basic assumption associated with conventional (stress/strength) reliability prediction is that the sum of the failure components (during the useful period) results in a constant failure rate (λ). This means that in order for the prediction to be valid:

- The item must reflect a mature design where design failures are not dominant.
- Quality (and early failures) problems have been minimized.
- Wearout is not noticeable or is beyond the period of concern.

In short, reliability predictive efforts that are based on or computed through conventional stress/strength prediction concepts reflect the reliability potential of a system or component item as it is expected to perform during its useful life period. These estimates depict the inherent reliability of the design as defined by its engineering documentation, basic stress/strength design factors and gross application, manufacturing, and quality factors. Note that these estimates do not represent actual use reliability unless the system or component item has reached complete maturity, where design failures have been eliminated and manufacturing and quality defects have been minimized. However, field experience has shown that this difference is due largely to quality related manufacturing flaws evident during the infant mortality period.

This infant mortality period may be caused by a number of things: gross built-in flaws due to faulty workmanship (manufacturing deviations from the design intent), transportation damage or installation errors. This initial failure rate is unusually pronounced in new hardware items. Many manufacturers provide a "burn-in" period for their product, prior to delivery, which helps to eliminate a high portion of the initial failures and assists in establishing a high level of operational reliability. Examples of early failures are:

- Poor welds or seals
- Poor connections
- Dirt or contamination on surfaces or in materials
- Chemical impurities in metal or insulation or protective coatings
- Incorrect positioning of parts.

Many of these early failures can be prevented by improving the control over the manufacturing process. Sometimes, improvements in design or materials are required to increase the tolerance for these manufacturing deviations, but fundamentally these failures reflect the "manufacturability" of the component or product and the control of the manufacturing process. Consequently, these early failures would show up during:

- In-process and final tests
- Process audits
- Life tests
- Environmental tests

As stated earlier, this report provides a methodology to evaluate qunatitatively the impact of production on reliability and in particular, the early failures and defects that give rise to infant mortality. It provides a means to minimize these early defects and/or flaws and to assure the reliability of an item as it is released to the field. The technique accounts for the contributions to unreliability of manufacturing processes, assembly methods and limited inspection capability, in addition to stress/strength design properties.

Specifically the methodology provides:

- a means by which the inherent reliability, as embodied in the design, can be retained during manufacturing.
- a means to determine the need for additional stress tests or better inspection.
- a technique to assure a smooth transition from design to production.
- the capability to assess, grow and control actual reliability during production.

1.2 Technical Approach

The methodology has been developed based on recognition that achievement of a high level of actual use reliability is a function of the effectiveness of production as well as design. As indicated in Section 1.1, design established the inherent reliability potential of a sytem and the transition from the paper design to hardware results in an acutal system reliability below this inherent level.

Accordingly, development of the reliability evaluation methodology has been approached first via design characteristics to establish an upper limit of reliability and then in conjunction with a series of factors that account for production degradation and its control.

Figure 1-3 illustrates conceptually the evaluation approach. The figure depicts the development of a helicopter system as it evolves from initial design, prototype development and test, production and release to operational use. The figure shows that an upper limit of reliability is established by design, that the reliability of initially fabricated hardware (prototype) will be degraded from this upper limit and improvement and growth is achieved through testing, failure analysis and corrective action. The figure further shows that as the helicopter system is released to manufacturing its reliability will again be degraded and as production progresses, with resultant process improvements and manufacturing learining factors, reliability will grow.

Figure 1-3 indicates that measures taken during the hardware development cycle enhance inherent reliability by forcing the design to be iterated, and minimize degradation by eliminating potential failures and manufacturing flaws prior to production and operational use. Design reliability efforts include selecting and specifying quality components, applying adequate design margins, incorporating load test techniques and/or designing redundancy into the system. They include both purchasing practices and specifications which insure the procurement of high quality material. They range from

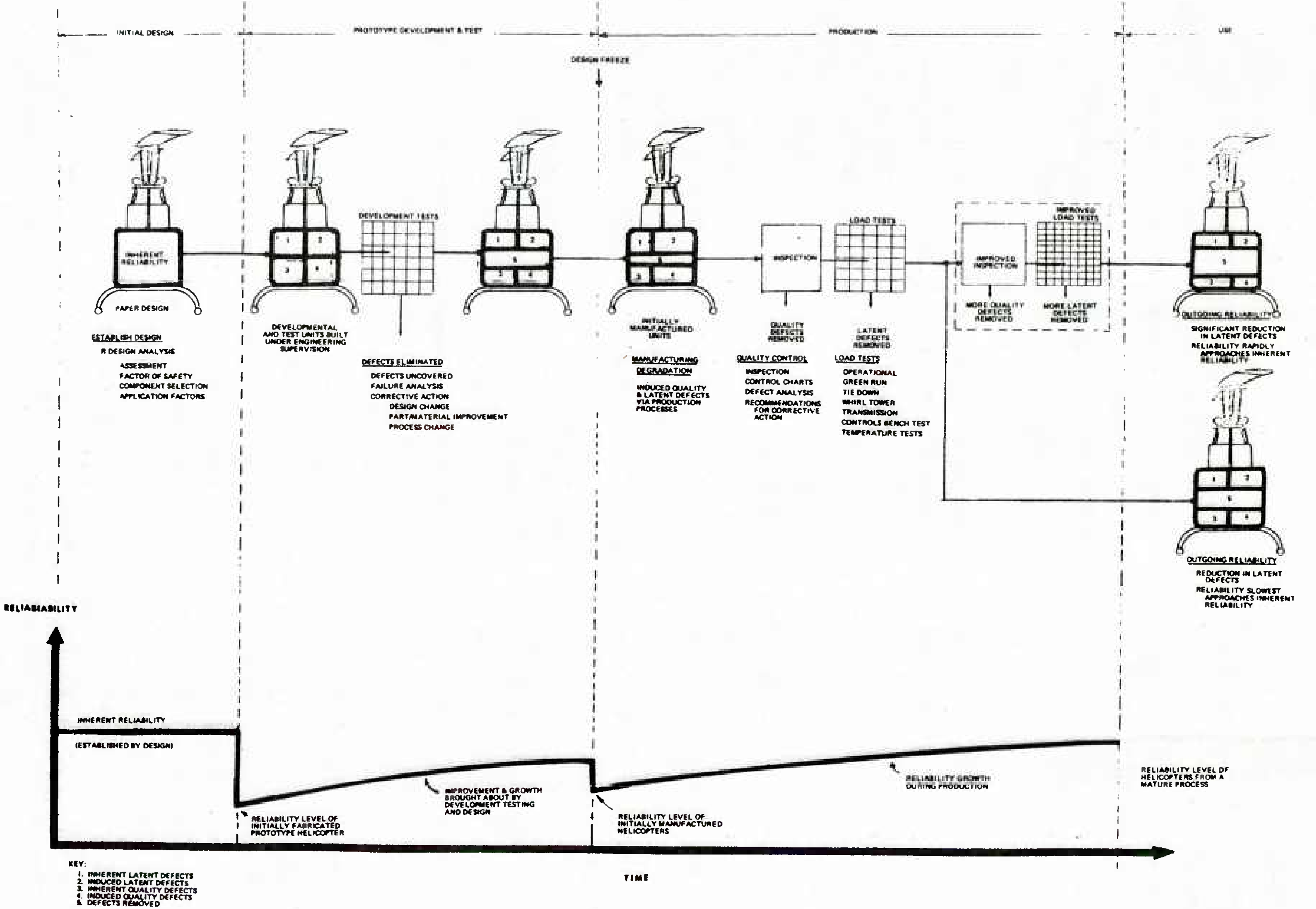


Figure 1-3 IMPACT OF DESIGN AND PRODUCTION ACTIVITIES ON HELICOPTER OUTGOING RELIABILITY

development of adequate test methods and assembly processes to development of effective formal systems for accurately reporting, analyzing and correcting failures which occur during use.

In a similar fashion, quality control activities begin during design but are predominant during the hardware fabrication process and are geared to eliminate defects which can cause failure during field use. These quality activities are associated with quality planning, material control and manufacturing control.

Figure 1-3 also shows that hardware unreliability is due to inherent component and material defects as well as defects induced by the production process. These defects, whether inherent to the design or induced by the process can be further categorized into (1) quality, and (2) latent reliability defects. The quality defect is generally apparent and detectable through standard inspection procedures. The reliability or latent defect is detectable only by application of stress. The quality defect, if not removed by efficient production process inspections, contributes strongly to infant mortality failures.

Consequently, the approach to determining reliability degradation due to production involves estimating the number of defects induced during fabrication and assembly processes and subtracting the number removed by quality control tests and inspections. The procedure requires quantifying the process induced defects including both quality and latent reliability and determining the effectiveness of quality control inspections and stress testing to remove the defects. This includes determining both the latent defects attributable to purchased components and materials as well as those due to faulty workmanship or assembly. These errors (as discussed in Section 1.1) can account for substantial degradation. Assembly errors can be brought about by inadequate operator learning, motivational or fatigue factors. Quality control inspections and tests are provided to minimize degradation from these sources and to weed out the more obvious defects. No inspection process, however, can remove all defects. A certain number of defective items will escape the process, be accepted and be placed in field operation. More important, these gross defects can be overshadowed by an unknown number of the latent reliability defects. These weakened items, the results of latent defects or inherent flaws, will fail under the proper conditions of stress — usually during field operation. Factory stress tests are designed to apply a stress of given magnitude over a specified duration to remove these kinds of defects. As in the case of conventional inspection processes, stress tests to remove latent defects are not 100% effective.

It must be emphasized (as shown in Figure 1-3) that reliability and quality degradation can be countered through implementation of formal efforts to control and grow reliability. Reliability growth is the formal action taken to hasten a hardware item toward its reliability potential either during development or during subsequent manufacturing. As previously stated, during early development the achieved reliability of a newly fabricated item, or an off-the-board prototype, is much lower than its predicted reliability. This is due to the initial design and engineering deficiencies as well as manufacturing flaws. The reliability control and growth process as defined by this study involves repetitive application of the evaluation methodology during the course of production and in particular during early production to identify (and measure) those processes and inspections where improvement would have the maximum impact in reliability.

The growth process involves consideration of hardware test, failure, correction and retest activities. Reliability growth is an iterative test-fail-correct process. There are three essential elements involved in achieving reliability growth, namely:

1. Detection of hardware failures and/or defects.
2. Feedback of problem areas.
3. Implementation or corrective action and retest.

The rate at which hardware reliability grows during production is dependent on how rapidly these three elements can be accomplished and, more importantly, how well the corrective action solves the problem identified. Specifically reliability grows during production as a result of corrective action that:

- Reduces process induced defect rates
  - manufacturing learning
  - improved processes
- Increases inspection efficiency
  - inspector learning
  - better inspection procedures
  - incorporation of screening (load) tests.

As process development and test and inspection efforts progress, problem areas become resolved. As corrective actions are instituted, the outgoing reliability, as measured by the evaluation methodology, approaches the inherent (design-based) value.

Thus, the reliability methodology can be an essential part of an effective reliability control and growth process and as such would allow management to exercise control, allocate resources and maintain visibility into process development and test activities — it can provide an effective and viable means to achieve a mature system prior to field use.

1.3 Scope and Contents of This Report

This report provides a methodology, modeling details and procedures for improving and controlling helicopter reliability for an item leaving production. It evaluates the infant mortality period during which manufacturing induced defects are dominant. The model computes reliability by estimating the number of outgoing defects from a detailed analysis of the fabrication and inspection process. The procedures take into account design and production factors with emphasis on production factors.

The proceeding paragraphs offer a brief description of the sections in this report.

Section 2 - discusses the design and fabrication characteristics of helicopters covering current production processes and quality control practices.

Section 3 - presents the basic probability considerations, modeling details, step-by-step procedures and data for assessing and controlling the reliability of helicopters leaving production.

Section 4 - provides sample calculations showing application of the methodology described in Section 3.

Section 5 - discusses reliability improvement and growth characteristics, identifies factors related to manufacturing learning and provides insights into improving the efficiency inspections and stress tests.

Section 6 - presents conclusions and recommendations resulting from this study.

Appendices - covers additional theory related to the methodology and a detailed plan for the establishment of an on-going data center.

2.0 RELIABILITY CHARACTERISTICS OF HELICOPTERS

Prior to presenting the mathematical foundations and the procedure for implementing the methodology it will be useful to briefly review helicopters to provide a historical perspective and to give an indication of those systems and components including their performance, design and fabrication characteristics which adversely impact reliability. Subsection 2.1 provides an overview of the development and evolution of helicopters from a performance and design standpoint. Subsection 2.2 briefly discusses helicopter manufacturing and inspection process characteristics.

2.1 Helicopter Development and Evolution

Helicopters can be defined as those aircrafts which derive both lift and propulsive force from a powered rotary wing and have the capability to hover and to fly rearward and sideward, as well as forward. Existing configurations used by the Army typically include a single lifting rotor with an antitorque rotor, and tandem lifting rotors.

The theoretical basis for rotary wing flight was first established in 1926. Analysis was at first confined to the autogyro, but by 1927 a theory of helicopter performance during vertical ascent was developed, which was then extended in 1928 to cover horizontal flight with the rotor axis vertical. By 1935 the analysis was extended to flight with the rotor axis inclined forward to give a component of rotor thrust for propulsion. Early experimental work centered around the autogyro, however by 1938, the era of the helicopter began to emerge when adequate controllability was first demonstrated by a helicopter in the hover mode. At this point it was clear that there were three main categories of rotary wing aircraft.

1. The classic or "pure" helicopter that had no separate means of propulsion, i.e., all of the power was supplied to the rotor or rotors.

2. The autogyro, whose rotor was kept in rotation during flight by aerodynamic forces only, the engine power being supplied to a propeller that provided a forward thrust component for translational flight. The rotor, thus was only a lifting device.

3. The compound or hybrid helicopter, in which part of the power was supplied to the rotor for producing lift and part to a propellor for providing propulsion. The addition of a fixed wing was used to reduce the lift component provided by the rotor in translational flight. This enabled higher

forward speeds to be achieved without encountering severe fluctuations in rotor life (periodic fluctuations, had in the past, been responsible for high rotor drag and inherent vibrational problems).

From 1940, up until the early 1960's, the overall performance capabilities of helicopters were relatively limited. However, beginning in the late 1950's, technological improvements, including reduction of parasitic drag, improved rotor systems, auxiliary propulsion, and lighter weight structures and engines, resulted in considerable growth in almost all aspects of helicopter operational capability. Figures 2-1 and 2-2 depict the improvements achieved in cruise speed and the reductions made in structural weight.

The increase in the spectrum of obtainable performance has since then had a major impact on military planning. New operational applications such as attack and heavy lift missions have become feasible and it is now possible to optimize configurations for particular classes of missions, rather than to use only one or two available helicopter types for a complete range of applications, as used to be the practice. Army helicopters today are classified according to the general mission they are developed to accomplish.

- Attack Helicopter (AH) - A fast, highly maneuverable heavily armed helicopter for combat fire support and helicopter escort missions. The attack helicopter can typically be a compound vehicle, i.e., with auxiliary forward propulsion and/or a stub wing used to unload the main rotor in high-speed flight.
- Cargo Helicopter (CH) - A medium or heavy lift class of helicopter that is intended primarily for heavy load-carrying missions. The loads may be carried internally or externally. These helicopters generally have a wide range of center of gravity (CG) travel.

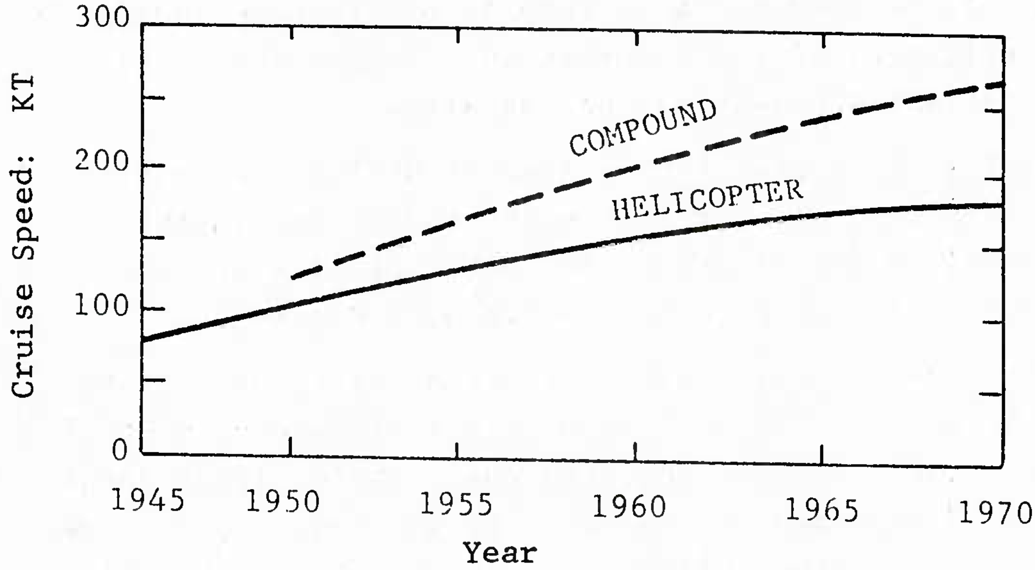


Figure 2-1 TRENDS IN HELICOPTER CRUISE SPEEDS [2]

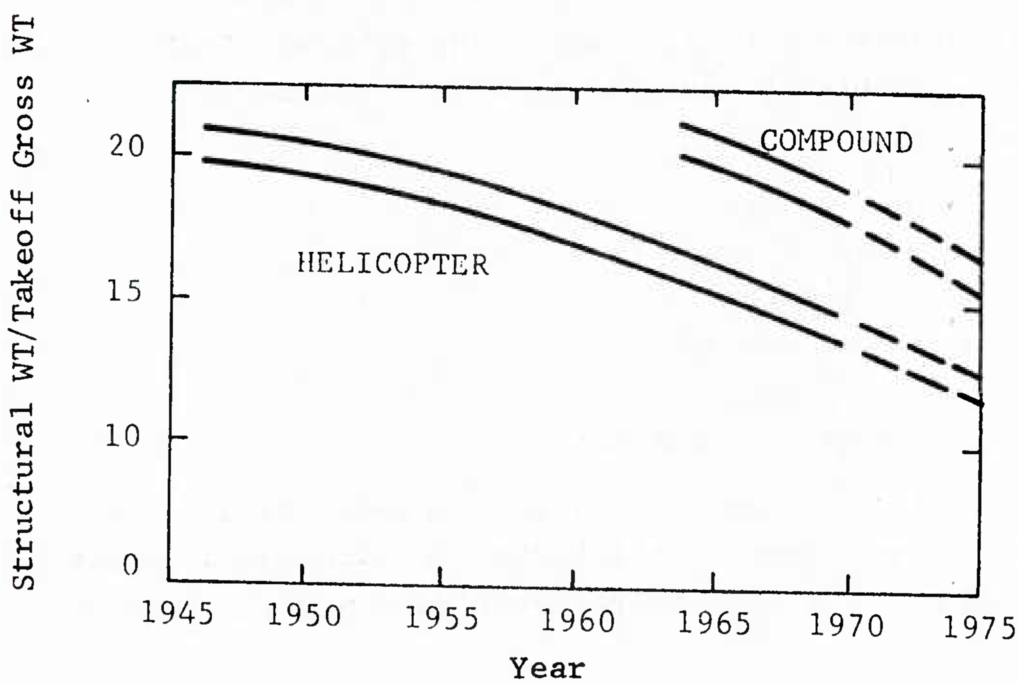


Figure 2-2 TREND OF STRUCTURAL WEIGHTS FOR HELICOPTERS [2]

- Observation Helicopter (OH) - A small, light machine that can be used for a variety of missions including surveillance, target acquisition, command and control, etc. Light armament may be installed.
- Training Helicopter (TH) - A small helicopter usually with seating only for instructor and student-pilot, or a helicopter of one of the other mission classes specifically assigned to the training mission.
- Utility Helicopter (UH) - A class of helicopter that is assigned a wide variety of missions such as medical evacuation, transporting personnel, and/or light cargo loads. Speed and maneuverability are required in order to minimize vulnerability when operating over hostile territory.

Basic data relating to the above classes of helicopters is shown in Tables 2-1, 2-2 and 2-3. Tables 2-2 and 2-3 respectively indicate the values of R and M estimated for fielded and developmental helicopters. The percent contribution of major helicopter components to direct maintenance costs are shown below:

- Air Frame 13%
- Power Plants 28%
- Flight Controls 5%
- Rotor Systems 11%
- Drive Systems 30%
- Remaining Systems 13%

The above data indicate that the dynamic components and the power plant as being primary contributors to maintenance costs. It should be pointed out that maintenance data usually include

Table 2-1 SELECTED ARMY HELICOPTERS [4] R=rad.of blade N=number

DESIG-NATION	NUMBER OF MAIN ROTOR BLADES	ROTOR RADIUS R (FT)	ROTOR DISC AREA (FT^2) πR^2	TYPICAL ROTOR ROTATION (RPM)	TYPICAL TIP SPEED $2\pi RN$ (FT/SEC)	MAXIMUM WEIGHT (LB)	MAX HP (SHP)
TH-55A	3	12.65	503	483	640	1670	180
OH-6A	4	13.17	545	483	666	2700	253
OH-58A	2	17.67	980	354	655	3000	317
UH-1C	2	22.00	1520	324	747	9500	1100
UH-1H	2	24.00	1009	324	814	9500	1450
AH-1G	2	22.00	1520	324	747	9500	1450
CH-47C	3 x 2	30.00	5655	245	770	46000	6050

Table 2-2 FIELDED AIRCRAFT SYSTEM RELIABILITY (R) FOR 1 HOUR

ACFT	SYSTEM R	SYSTEM MTBF	MISSION R	MISSION MTBF	MMH/FH
CH54A	.7304	3.18	.9845	64.01	7.43
CH47C	.7130	2.96	.9716	34.71	5.79
AH1G	.7515	3.50	.8926	8.80	4.50
OH6	.6884	6.97	.9967	302.53	4.45
OH58	.6884	6.97	.9967	302.53	4.60
UH-1H	.7228	3.08			

No satisfactory data exists for OV-1 and U-21.

Table 2-3 DEVELOPMENTAL SYSTEM RELIABILITY (R) FOR 1 HOUR

ACFT	SYSTEM R	SYSTEM MTBF	MISSION R	MISSION MTBF	MMH/FH
UTTAS	.7788	4.00	.9870	76.42	4.20
AAH	.7000	2.80	.9500	19.50	8.00
HLH	None		.9849	65.72	7.39
214	.9750	4.36			

maintenance and operator damage, equipment scavenging and failures due to environmental causes. During the initial deployment phase, as many as 50% of the maintenance removals of some components have actually been proven to be good units. [4] The accessibility of components has considerable impact on their removal or repair rate. This has been observed on fuel subsystems, for example, where direct maintenance on the fuel control unit is difficult when the engine is installed in the aircraft.

The failure modes associated with the dynamic components and which give rise to their high maintenance support costs are:

- <u>Engine Failure Modes</u> (See Table 2-4)

  Inspection of Table 2-4 indicates that bearings and seal failures account for the greatest number of engine removals. Bearing and fuel problems are the leading causes of major helicopter flight safety incidents, while combustion and turbine failures require the largest maintenance manpower

- <u>Transmission Failure Modes</u> (See Table 2-5)

  Typical components and parts that make up a transmission assembly include:

  - <u>Bearings</u> - Bearing failures contribute significantly to transmission unreliability. Bearing failures are often involved in engine failure modes.
  - <u>Gear Teeth</u> - Surface fatigue (spalling) of gear tooth profiles relates to the corresponding phenomena in bearings, although the probability of its occurrence is less. While seldom catastrophic, gear spalling is recognized as potentially being a nucleus for a more serious tooth fatigue failure, if not discovered and corrected.
  - <u>Gear Mountings</u> - Particularly in bevel gearing, the attachment of the gear to the shaft through splines or bolts may be prone to fretting deterioration.

Table 2-4 R&M CHARACTERISTICS OF A TYPICAL TURBINE [1]

	Subsystem	MTBR* (HRS)	MTBSI ($x10^5$ HRS)	MMH ($x10^{-3}$)	TBO
Engine Caused	Bearings	9500	2.5	3.5	12%
	Seals	5000	25.0	4.7	
	Compressor	14000	2.1	4.0	63%
	Combustion	25000		19.6	
	Turbine	17000	4.3	19.6	25%
	Cases	185000	100.0	1.5	
	Lubrication	30000	20.0	2.1	
	Fuel	12000	2.1	9.8	
	Air	100000		.2	
	Accessories	40000	14.0	2.3	
	Torquemeters	21000	50.0	.7	
	Electrical	70000	100.0	3.9	
	Exhaust	250000		.7	
	Power Train	77000	33.0	.4	
	Subtotal	(1406 hrs)	(55,045 hrs)	(.073 mmh/flt hr)	
Nonengine Caused	Environment	1700	2.1	1.9	
	Human Error	2300	3.7	9.2	
	Airframe Related	6700	33.0	2.4	
	Scavenging	2000		9.5	
	Unknown	2800	.70	8.5	
	Subtotal	(493)	(45,345 hrs)	(.032)	
	Total	(365 hrs)	(24,863 hrs)	(.105 mmh/flt hr)	

* MTBR--Mean Time Between Unscheduled Engine Romoval
MTBSI--Mean Time Between Major Safety Incidents
MMH--Maintenance Man Hour Rate
TBO--Time Between Overhaul

Fretting is a time dependent phenomenon and exists at nearly every unlubricated interface to a degree; whether that degree is tolerable for a particular interface depends upon the severity of the fretting.

- <u>Housings</u> - Cracks have occured in magnesium cases. Occasionally they are the result of random flaws in material and processing, but more often they occur in unflawed castings as the result of vibratory stresses introduced externally.

- <u>Seals</u> - Seals exhibit a wearout failure mode that results in leakage, and are additionally sensitive to handling and external environment.

- <u>Spacers, Bearing Liners and Retention Hardware</u> - Spacers, liners and other components required to locate bearings have proven to have high failure rate wear problems. Bearing locknuts and other retention hardware have occasionally backed off, sometimes with catastrophic results. A high proportion of locknut failures involve maintenance error, hence failures may be related to the maintenance interval.

Table 2-5 PERCENT CONTRIBUTION TO TRANSMISSION REMOVALS [4]

CH-47		CH-53	
Bearing Spacer Wear, etc.	55%	Bearings	30%
Operation (FOD, over stress, etc.)	20%	Gears	30%
Leaks	5%	Loose Locknuts	15%
Gears	5%	Lubrication Hardware	25%
Loose Locknuts	15%		

- Drive Shaft Failure Modes (See Table 2-6)
- Rotor Head Failure Modes (See Table 2-7)
- Rotor Control Failure Modes (See Table 2-8)
- Rotor Blade Failure Modes (See Table 2-9)

Teble 2-6 DRIVE SHAFT FAILURES AND CAUSES [6]

No.	Feilure Mode	Cause	MTBF (hrs)
1	Shaft Adepter Crack	Fetigue	50,000
2	Sheft Adapter Crack	Fatigue in Fretted Hole	1,000
3	Sheft Slot Elongeted	Inedequate Clearance	3,000
4	Coupling Cap	Maintenence Demage	1,000
5	Scratches & Gouges	Main. Demage	500
6	Cracked Coupling Plate		5,000
7	Spline Wear		1,000
8	Bearing Feilure	Misalignment	1,000
9	Sheared Retainer		5,000
10	Water Entrapment	No Dreinege Provisions	10,000
11	Sheared Rivets	Main. Damage	3,000
12	Shaft Vibretions	Poor Spline Lube	1,000
13	Shock Mounts Worn	Dirt & Contamination	500
14	Mount Spring Failure	Excessive Deflection	100
15	Worn Sheft Bushing	Improper Heat Treat	500
16	Thrust Bearing Spell		3,000
17	Couged Shaft	Main. Error	3,000
18	Hut Thread Damage	Main. Damage	50,000
19	Beering Oil Line	Main. Error	10,000
20	Bearing Seal Leekege		3,000
21	Improper Instelletion	Main. Ass'y Error	100,000
22	Mount. Bushing Cracked	Flexing Aircraft	500
23	Mount. Spring Slips	Flexing Aircraft	500
24	Bearing Reteiner Crack	Reverse Thrust	1,000
25	Rivets Sheared	Design Deficiency	3,000

Tebls 2-7 ROTOR HEAD FAILURES AND CAUSES [6]

No.	Failure Mode	Cause	MTBF (hrs)
1	Interposer Supports Broken		500
2	Gep Between Tie Bar and Washer	Rotor Overspeed	3,000
3	Tie Bar Pin Fractured	Stress Corrosion	100,000
4	Droop Stops Bent, Distorted & Missing	Blade Flapping	1,000
5	Thrust Washer Calling		500
6	Seal Unseated	Mfg., Out of Tolerance	50,000
7	Seal Leaking		3,000
8	Seal Leaking	Sand Erosion	500
9	Seal Leaking		3,000
10	Bearing Roller, Crinding Undercuts	Mfg. & Quality Control	100
11	Sight Cup Cracked and Broken	Pressure, Temperature & Maintenance	100
12	Vertical Pin Seizing		500
13	Vertical Pin Cracked	Material Defect	100,000
14	Retaining Nut Backing Off		100,000
15	Limited Chafing Crooves in Tanks	Aircraft Vibration	500
16	Droop Stop Wear	Aircraft Vibration	500
17	Spring Leaf Bent and Broken		1,000
18	Tank Assembly Corrosion	Dissimilar Metals	10,000
19	Droop Stop Clevis Broken	Overtorque of Bolts	100
20	Pitch Housing Cracked	Stress Corrosion	100,000
21	Housing Cracked	Stress Corrosion	100,000
22	Pitch Bearing Race Displaced	Maintenance Procedures	100
23	Pitch Shaft Cracked	Operational Error	3,000
24	Bearing Spalling		5,000
25	Bearing, Brinelling and Spalling		5,000
26	Bearing Spalling		3,000
27	Bearing Corroded		3,000
28	Bearing Cage Damaged		5,000
29	Rotor Nut Hot Reusable	Hylon Insert Wear	100
30	Flange Bearing Scuffed	Pitch Link Rotation	5,000
31	Spacer Deleted at Installation	Maintenance	100

Teble 2-8 ROTOR CONTROL FAILURES AND CAUSES [6]

Ho.	Failure Mode	Cause	MTBF (hrs)
1	Swashplate Oil Leak		100
2	Swashplate Ball Dislodging	Inadequete Bonding	500
3	Ball Race Rotating	Inadequate Bolt Preload	500
4	Wear of Teflon Bearings	Rough Surfaces	1,000
5	Flaking of Ball and Slider	Quality Control	500
6	Wear of Ball and Slider	Dirt Contamination	1,000
7	Bearing Spalling		1,000
8	Interference of Actuators	Lockout Blocks Not Used	1,000
9	Retainer Displacement	Lockout Blocks Not Used	10,000
10	Bolt Failure	Meterial Defect	100,000
11	Clevis Scoring	Rotation of Pitch Links	500
12	Cracked Bushing	Material Defect	3,000
13	Drive Collar Cracks	Excessive Air Loads	5,000
14	Rainshield Cracks	Manufacturing Error	500
15	Rainshield Deflects	High Forward Speed	100
16	Bearing Wear		100
17	Boot Material Deterioration		1,000
18	Sight Cage Class Loose	Insufficient Edge Crimping	5,000
19	Oil Seal Separates	Different Temperature Expansion	100
20	Lower Ring Cracking	Tool Marks	3,000
21	Cage Scraping Race	Faulty Installation	100
22	Rainshield Cracked	Maintenance Damage	100
23	Rainshield Contacted by Arm.	Rainshield Mfg. Error	100

Teble 2-9 ROTOR BLADE FAILURES AND CAUSES [6]

Ho.	Failure Mode	Cause	MTBF (hrs)
1	Delamination of Rib Tabs		500
2	Rib Cracking		1,000
3	Tip Cover Cracking	Alternating Air Loads	500
4	Tip Cover Erosion		1,000
5	Tie Fitting Cracked		30,000
6	Trailing Edge Cracking	Nicks on Forward Edge	30,000
7	Spar Doubler Unbonding	Temperature and Humidity	30,000
8	Spar Corroded	Inadequate Protective Coating	1,000
9	Water Entrapment		[illegible]
10	Incident Bolt Hole Cracked	Burr in Hole	100,000
11	Skin Erosion		
12	Delamination of Doubler	Air Flow	1,000
13	Spar Crack	Excess Blade Flapping	100,000
14	Incidence Bolt Corrosion	Inadequate Protective Coating	30,000
15	Incidence Bolt Fretting		3,000
16	Leading Edge Erosion		1,000
17	Tip Studs Corroded		5,000
18	Fairing Erosion		1,000
19	Skin Delamination	Skin Ply Orientation in Error	3,000
20	Hysol Filler Flaking		1,000
21	Span Crack	Due to Rolling Process	100,000
22	Tip Weight Fitting Unbonding	Poor Quality Control	500
23	Tip Weight Studs Unbonded	Poor Quality Control	10,000
24	Nut Plates Pulled Out	Poor Quality Control	3,000
25	Water Entrapment	Lack of Drainage Holes	100
26	Rib Tab Unbonding	Manufacturing Procedures	3,000

Future helicopter trends and reliability and maintainability characteristics now seem to be predicated on a number of innovations, among which are included in the following:

- Composite materials - The widespread use of composites in the next generation of helicopters might permit low cost tailoring of shape versus span, greatly increased tolerance to damage, whether from gunfire or impact, and reduce the complexity and hence, the cost of such traditionally high cost components as tail rotor systems and main rotor blades.

- Metallurgical developments - The development and successful adaptation of high hardness materials to such components as transmission gearing could permit helicopter main transmission assemblies to handle approximately 20% more power at approximately 10% less weight. Such assemblies and other dynamic components also are being used which will need little or no lubrication and which, in emergency situations, will be able to operate for periods without any lubrication.

- Maintenance Warning systems - Such systems are already beginning to appear in present day helicopters and are scheduled for increased use in the next generation of rotary-wing aircraft. These systems are self-checking systems that will warn the operator when they have reached the end of their useful life. This will aid the trend to major sybsystems that can be removed or overhauled on an "on-condition" basis, rather than on a specific timetable.

- Increased overhaul periods - The next generation of helicopters could have significantly increased time between overhaul periods for such dynamic components as rotors, transmissions, controls and drive shafts, with the trend to eliminating specific periods altogether and going to an "on-condition" basis for overhaul.
- Fly-by-wire control systems - Fly-by-wire control systems are also expected in the next generation of helicopters for increased reliability at weight and space savings of up to 50%.
- Noise and vibration reduction - The use of tailoring composite materials, may even permit drastic reductions in the rotor noise of the next generation of helicopters, possibly the total elimination of the familiar rotor slap. Developments in dynamic isolation might permit reductions of vibration by up to 60% over present day helicopters. This in turn could lead to substantial reductions in total maintenance man hours.
- High-lift airfoils - High-lift rotor air foils have been derived primarily from the supercritical wing technology and subsequently tailored for helicopter use. These show promise of increasing the coefficient of lift from 10-50% over present helicopters.

2.2 Helicopter Manufacturing Processes

In contrast to other industries where high volume production, rapid assembly and automation are the keynote, helicopter assembly processes differ in several respects. Helicopters are essentially handmade vehicles whose production involves the use of numerous jigs, fixtures and other fabrication aids for the worker. Worker skill plays a greater role in helicopter production especially in airframe construction where structural integrity (to a large extent) can be tied to individual craftsmanship.

The elimination of human error and assurance of quality fabrication depends strongly on careful and continuous inspection. The helicopter is inspected while the assembly operations are in progress — especially welds, fasteners and other structural members which become hidden by subsequent fabrication operations. During assembly operations, each air-frame (and also the major components) acquires a production documentation package which records the production and inspection sequence and which forms a permanent record for that airframe.

The parts and components which comprise helicopters are also somewhat unique in that extensive material/process certifications are required of the manufacturer, more inspection is required prior to acceptance and only limited quantities are produced. Limited production is especially true of structural parts not subject to wearout, periodic replacement or having sparing requirements as part of the maintenance supply pipeline.

In conjunction with manufacturing processes in general and as specifically related to the production of helicopters, three levels of manufacturing are defined. Table 2-10 provides a partial listing of the kinds of processes which characterize each manufacturing level. Note that the three levels correspond to the processing of basic raw materials into rough shapes, processing the rough shapes into finished parts and finally the assembly of finished parts into the desired end item.

Table 2-10 MANUFACTURING PROCESSES CHARACTERIZED BY LEVEL

Manufacturing Level	Manufacturing Process
Primary	• Casting • Forging • Extending • Bending • Shaping • Forming
Secondary	• Material Removal • Cutting • Machining • Heat treating • Cleaning • Coating
Tertiary	• Welding • Chemical joining • Soldering • Bolting

As an example of how these three levels are used to define complex production processes consider Figure 2-3 and 2-4 which depict the manufacture of honeycomb filler used in helicopter rotor blades and actual assembly of the rotor blade itself.

As indicated in these figures, the manufacture of honeycomb can be traced from a primary fabrication process involving shaping of the sheet material to a secondary process level which involves cleaning, surface preparation, and adhesive application and then to a tertiary fabrication level involving subassembly of the constituent sheets for the honeycomb core. The final assembly is illustrated in Figure 2-4, where the honeycomb core is assembled with other components to make up the finished rotor blade.

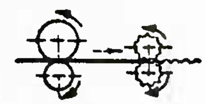
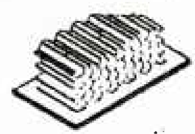
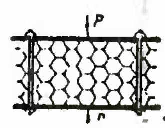
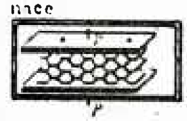
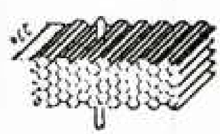
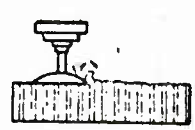
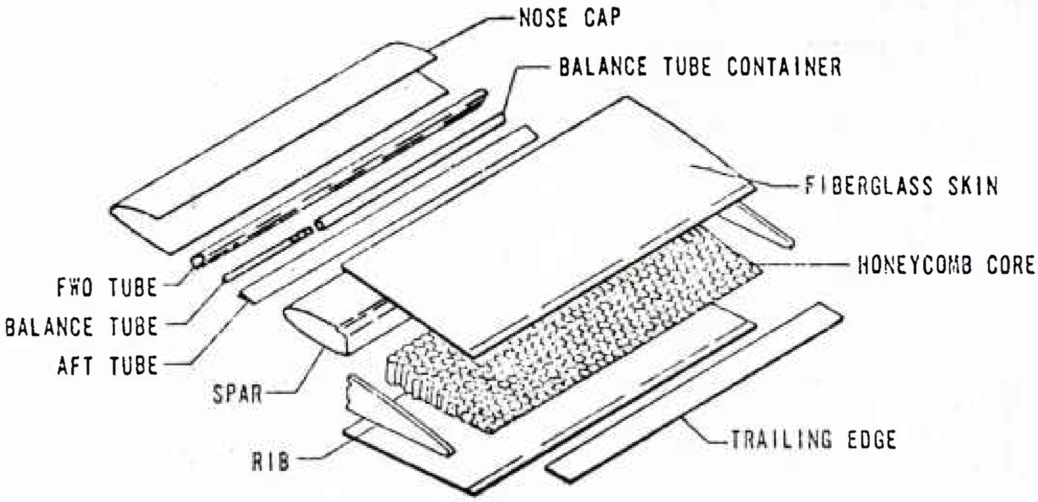
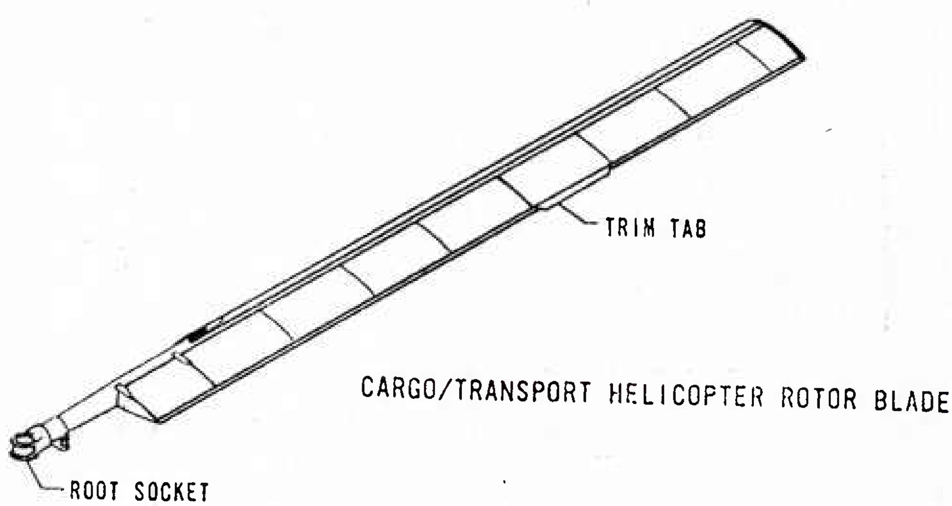
Level	Operation	Sketch
Primary	Shaping of the foil and formation of pressure-tap holes	
	Formation of assembly-line holes	
Secondary	Degreasing and drying of the foil.	
	Applying the glue and drying	
Tertiary (Sub-Assembly)	Assembly of the unit on assembly-line holes	
	Pressing of the unit	
	Hardening of the glue	Electric air-circulating furnace 
	Cutting of the unit into billets of the necessary dimension	
	Milling of the honeycomb filler	
	Checking (the realization of each opera- is checked)	

Figure 2-3 THREE BASIC LEVELS INVOLVED IN MANUFACTURING ROTOR BLADE HONEYCOMB FILLER



Tertiary (Final-Assembly)



Finished Item

Figure 2-4 EXAMPLE OF A TERTIARY PROCESS (AND THE FINISHED ITEM) INVOLVING ROTOR BLADE ASSEMBLY

The definition of the three manufacturing levels provides a useful method of cataloging production processes. In addition they provide the basis for describing repeatability numerics.[7] Repeatability is a number between 0 and 1 which describes the likelihood of the process to produce items of a predefined quality. Values of repeatability can be used to estimate the probability of defects entering a given item as a result of a particular process and therefore characterizes the reliability of the item as it leaves the production line.

Tables 2-11, 2-12, and 2-13 provide detail concerning process repeatability. Referring to Table 2-11, Columns 4 and 5 provide repeatability and non-repeatability data at the primary manufacturing level. Column 2 lists the kinds of imperfections caused by the process and which influence the magnitude of the non-repeatability numeric. Tables 2-12 and 2-13 show the same type of information for the remaining manufacturing levels. The topic of process induced defects and estimates of their magnitude from repeatability numerics is treated in Section 3 of this report.

Table 2-11 REPEATABILITY NUMERICS AT THE PRIMARY LEVEL

1 GENERAL PROCESS	2 INDUCED IMPERFECTIONS	3 SPECIFIC PROCESS	4 REPEATABILITY	5 NONREPEATABILITY
CASTING	Voids, Stress, Inclusions, Low Strength, Roughness	Sand	90%	.10
		Plaster Mold	90%	.10
		Investment	90%	.10
		Permanent Mold	90%	.10
		Die	90 - 95%	.10-.05
		Continuous	90%	.10
		Centrifical	95%	.05
FORGING	Stress, Inclusions, Hardness, Cracks	Powder Metallurgy	95%	.05
		Open Die	95%	.05
		Closed Die	95%	.05
		Upset	95%	.05
EXTRUDING	Stress, Cracks, Voids	Cold Heating	99%	.01
		Impact	99%	.01
		Cut	99%	.01
		Roll Forming	99%	.01
BENDING	Stress, Cracks, Embrittlement	Forming	99%	.01
		Spinning	95 - 99%	.05-.01
		Explosive-forming	99%	.01

Table 2-12 REPEATABILITY NUMERICS AT THE SECONDARY LEVEL

GENERAL PROCESS	INDUCED IMPERFECTIONS	SPECIFIC PROCESS	NONREPRODUCEABILITY
MATERIAL REMOVAL	Inclusions, Work Hardening, Nicks, Burrs, Surface Roughness, Stresses	Boring	.003-.004
		Broaching	.003-.004
		Drilling	.006-.008
		Hobbing	.03-.16
		Milling	.002-.08
		Reaming	.004-.008
		Turning	.002-.08
		Grinding	.004-.04
		Cutting	.003-.004
		Punching	.003-.004
		Tumbling	.003-.08
HEAT TREATING	Brittleness, Residual Stresses, Hardness-Depth/Uniformity	Hardening	.008-.04
		Annealing	.003-.004
CLEANING	Contamination, Corrosion Material Removal	Grinding/Sanding	.002-.008
		Brushing	.002-.008
		Abrasive Blasting	.002-.04
		Steam or Flame	.002-.008
		Electrolytic	.002-.016
		Ultrasonic	.001-.004
		Organic Solvent	.002-.008
		Alkaline	.002-.04
		Acid	.002-.04
COATING	Poor Bonding, Non-uniformity	Metallurgical	.001-.08
		Diffusion	.002-.004
		Electrochemical	.002-.004
		Chemical	.002-.004
		Mechanical	.002-.004

Table 2-13 REPEATABILITY NUMERICS AT THE TERTIARY PROCESS LEVEL

GENERAL PROCESS	INDUCED IMPERFECTIONS	SPECIFIC PROCESS	NONREPRODUCEABILITY
WELDING	Voids, Residuals, Stresses, Cracks, Warpage	Arc	.05-.20
		Laser	.05-.10
		Gas	.05-.10
		Thermit	.10-.20
		Electron Beam	.01-.05
		Resistance	.05-.20
CHEMICAL JOINING	Reduced Strength, Voids, Non-uniformity	Natural Adhesives	.006-.04
		Thermoplastics	.001-.08
		Thermosetting	.001-.08
		Elastomeric	.001-.08
SOLDERING	Low Strength, Non Aderhence	Resistance	.001-.05
		Thermal Contact	
		Sweat	
BOLTING	Loudness Over Torque	Captive	.001-.10
		Bolt/Nut	
		Safety Wire	

3.0 RELIABILITY AND QUALITY CONTROL DURING PRODUCTION

The reliability of an item as it leaves production, in general, is dependent on the defects induced less the defects removed by the manufacturing processes. The amount of defects left in the item as it leaves production (or the degree of reliability degradation) can be determined by assessing the number of defects introduced with respect to the effectiveness of their removal. To assess this degradation in quantitative terms requires: (1) the development of a theory for associating probabilities of defect introduction and defect removal with existing inherent defect contents; (2) definition of a user oriented procedure for applying this theory to typical production schemes, and (3) establishment of a data base to validate the theory and allow predictions to be made from the theory when actual production data is not available.

Each of these requirements were studied in detail during the course of this effort and the results are presented in this section.

Subsection 3.1 Probability Considerations - A notation is presented for associating probabilities with production processes. Equations are developed which predict outgoing defect rates for generalized manufacturing process configurations.

Subsection 3.2 Procedure - A step-by-step user oriented procedure is provided for assessing production degradation. The procedure can be used to assess on-going production processes as well as to assess production processes planned for newly developed hardware items.

Subsection 3.3 Data Base - Data tabulations are presented for those parameters required as input to the production degradation assessment procedures. A rationale is discussed for the application of this data.

3.1 Probability Considerations

This section considers the theoretical aspects of how defects enter parts, how they are removed and resultant defect concentration. Defects are defined as weaknesses which reduce a part's strength and thereby increase its probability of failure.

The approach taken in this section is to divide the defects and manufacturing system into their basic components, develop the probability considerations for those components, and then incorporate the probability considerations into a unified theory for evaluating the impact of defects on failure rate.

For simplicity, in order to aid in the discussion of this section, the word "unit" will be used to describe either a part, component, subsystem or system.

3.1.1 The Manufacturing System and Process Symbols

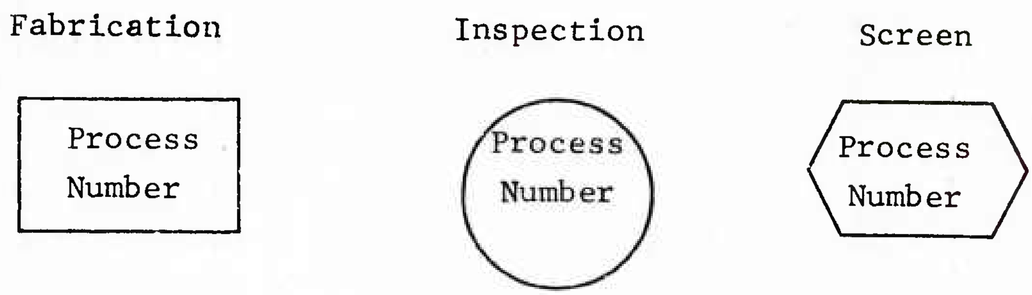
A manufacturing process can be divided into four basic components:

- Fabrication - The processes associated with bringing a unit from raw materials to the finished units. These processes can be further categorized into primary, secondary, and tertiary manufacturing levels as described in Section 2.2.

- Inspection - The processes associated with the examination of units (either manual or automatic) to detect and remove defective units.

- Loading - The processes associated with the application of stress to a unit to force weak parts (which would fail prematurely in the field) to fail in the factory. If inspection is associated with loading the process is often referred to as a screen test.

For purposes of modeling and development of probability equations in later sections, a standard set of symbols for each manufacturing process was developed and is given below.



In addition to the process identification numbers inside the symbols, relevant numerical information (which will be discussed in subsequent sections) will be included.

3.1.2. <u>Defect Types and Probability Notation</u>

Defects were defined above as flaws or imperfections which weaken units and thereby increase the probability of failure. There are two basic types of defects that can be introduced during a manufacturing process:

- Quality Defect - A defect that can be found without loading the unit and with inspection equipment and procedures normally available to a quality control inspector.

- Latent Defect - A defect that can be found only by loading the unit and not detected by the inspection equipment and procedures normally available to a quality control inspector.

The quality control function is dedicated to eliminating quality defects using conventional inspection equipment and techniques. The elimination of latent defects requires the addition of more sophisticated equipment capable of loading the unit.

A notation system was developed in order to facilitate the calculation of the defect rates (probability that a part contains a defect) at any point during a manufacturing process.

Q_i - Quality defect

L_i - Latent defect

i - Subscript indicating a point in the manufacturing process

q_i - A quality defect induced by process i

l_i - A latent defect induced by process i

$P(Q_i)$ - Probability of a quality defect being in a unit after process i and before process i+1

$P(L_i)$ - Probability of a latent defect being in a unit after process i and before process i+1

$P(q_i)$ - Probability of a quality defect being induced in the unit during process i

$P(l_i)$ - Probability of a latent defect being induced in the unit during process i

$P(E|Q)$ - Probability of detecting a quality defect by inspection, given the defect is present

$P(S|L)$ - Probability of converting a latent defect to a quality defect through loading, given that a latent defect exists.

A further simplification of notation occurs if the event notation is used to denote the probability or:

$$Q_i = P(Q_i) \tag{3-1}$$

$$L_i = P(L_i) \tag{3-2}$$

$$q_i = P(q_i) \tag{3-3}$$

$$l_i = P(l_i) \tag{3-4}$$

$$E = P(E|Q) \tag{3-5}$$

$$S = P(S|L) \tag{3-6}$$

For the procedure and sample applications of Sections 3 and 4, the simplified notation will be used exclusively; therefore, it is introduced here.

The complement of an event A is denoted as Â and the probability of A not occuring is given by

$$P(\hat{A}) = 1 - P(A) \qquad (3\text{-}7)$$

3.1.3. Probability Considerations for Fabrication Processes

Manufacturing processes have been categorized into primary, secondary, and tertiary levels. This section will develop the probability considerations for introducing and removing quality defects and latent defects for processes or combinations of processes in each of these levels. In addition, a simplified set of equations and notation will be included for cases where the defect probabilities are small numbers.

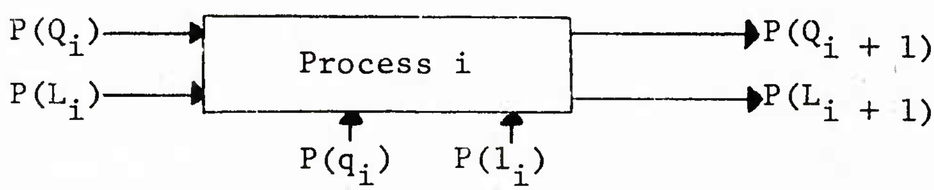
ONE STEP FABRICATION PROCESS

A one step process might be encountered:

- as part of a larger fabrication process
- if the unit consists of one part and only one fabrication step is required.

The one step process is also used to generalize the more complicated process steps.

Consider a process as shown below.



PROBABILITY DIAGRAM FOR ONE STEP PROCESS

The relationships between incoming and outgoing defects from the process are given in the following equations.

$$P(Q_{i+1}) = P(Q_i) + P(q_i) - P(Q_i)P(q_i) \qquad (3\text{-}8)$$

$$P(L_{i+1}) = P(L_i) + P(l_i) - P(L_i)P(l_i) \qquad (3\text{-}9)$$

and when

$$P(Q_i) + P(q_i) \gg P(Q_i)\,P(q_i) \tag{3-10}$$

$$P(L_i) + P(l_i) \gg P(L_i)\,P(l_i) \tag{3-11}$$

then

$$P(Q_{i+1}) = P(Q_i) + P(q_i) \tag{3-12}$$

$$P(L_{i+1}) = P(L_i) + P(l_i) \tag{3-13}$$

Expressing equations (3-12) and (3-13) in the simplified notation of Section 3.2.

$$Q_{i+1} = Q_i + q_i \tag{3-14}$$

$$L_{i+1} = L_i + l_i \tag{3-15}$$

Example Consider a manufacturing system that consists of a one step process with defect probabilities given below.

$$P(Q_o) = 0.02$$

$$P(L_o) = 0.02$$

$$P(q_i) = 0.05$$

$$P(l_i) = 0.05$$

Then the outgoing probabilities from equation (3-8) and (3-9) are given below

$$P(Q_i) = 0.069$$

$$P(L_i) = 0.069$$

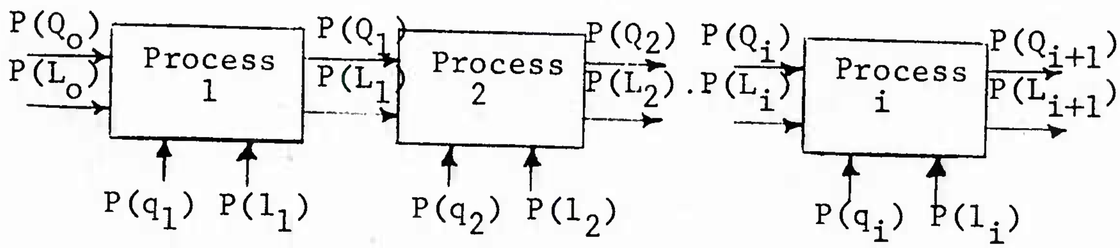
and using equations (3-12) and (3-13) (which implies small values for defect probabilities)

$$P(Q_i) = 0.070$$

$$P(L_i) = 0.070$$

SERIES OF PROCESS STEPS

This situation is encountered when a unit is manufactured by a series of process steps and no additional units are combined (or assembled) with it during the process. Consider the process shown below.



PROBABILITY DIAGRAM FOR A SERIES OF PROCESSES

The relationship between the incoming and outgoing defect probabilities are given below.

$$P(Q_{i+1}) = 1 - P(\hat{Q}_o) \prod_{j=1}^{i} P(\hat{q}_i) \tag{3-16}$$

$$P(L_{i+1}) = 1 - P(L_o) \prod_{j=1}^{i} P(\hat{l}_i) \tag{3-17}$$

and when the defect probabilities are small

$$P(Q_{i+1}) = \sum_{j=1}^{i} P(Q_j) \tag{3-18}$$

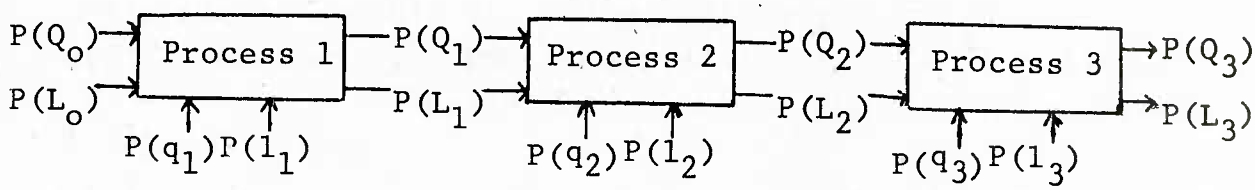
$$P(L_{i+1}) = \sum_{j=1}^{i} P(L_j) \tag{3-19}$$

Expressing equations (3-18) and (3-19) in the simplified notation of Section 3.2.

$$Q_{i+1} = \sum_{j=1}^{i} Q_j \tag{3-20}$$

$$L_{i+1} = \sum_{j=1}^{i} L_j \tag{3-21}$$

Example: Consider a manufacturing system as shown below.



SERIES OF PROCESSES EXAMPLE

The incoming and process induced defect probabilities are given as

$$P(Q_o) = 0.02$$

$$P(L_o) = 0.02$$

$$P(q_1) = P(q_2) = P(q_3) = 0.05$$

$$P(l_1) = P(l_2) = P(l_3) = 0.05$$

The outgoing defect probabilities are given by equations (3-16) and (3-17) as:

$$P(Q_3) = 0.16$$

$$P(L_3) = 0.16$$

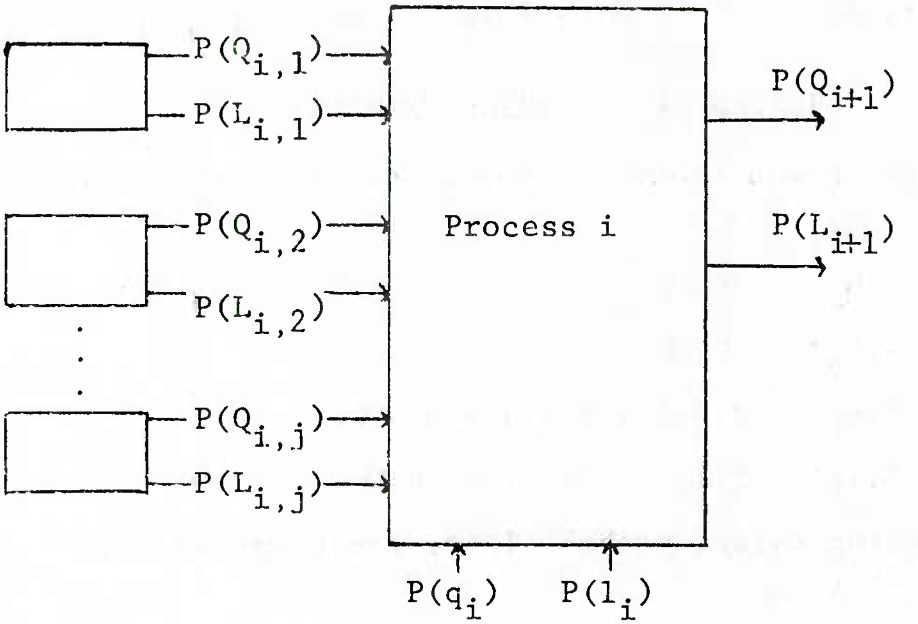
and using equations (3-18) and (3-19) which implies small values for defect probabilities

$$P(Q_3) = 0.17$$

$$P(L_3) = 0.17$$

AN ASSEMBLY PROCESS

In an assembly process, parts containing defects are assembled and defects can be induced during the assembly process. Consider the assembly process shown below.



PROBABILITY DIAGRAM FOR AN ASSEMBLY PROCESS

In the above diagram, the second subscript identifies the component parts of the assembly. The relationships between incoming and outgoing defect probabilities for an assembly process are given in the following equations.

$$P(Q_{i+1}) = 1 - P(\hat{q}_i)\prod_{k=1}^{j} P(\hat{Q}_{i,k}) \tag{3-22}$$

$$P(L_{i+1}) = 1 - P(\hat{l}_i)\prod_{k=1}^{j} P(\hat{L}_{i,k}) \tag{3-23}$$

and when the defect probabilities are small

$$P(Q_{i+1}) = P(q_i) + \sum_{k=1}^{j} P(Q_{i,k}) \tag{3-24}$$

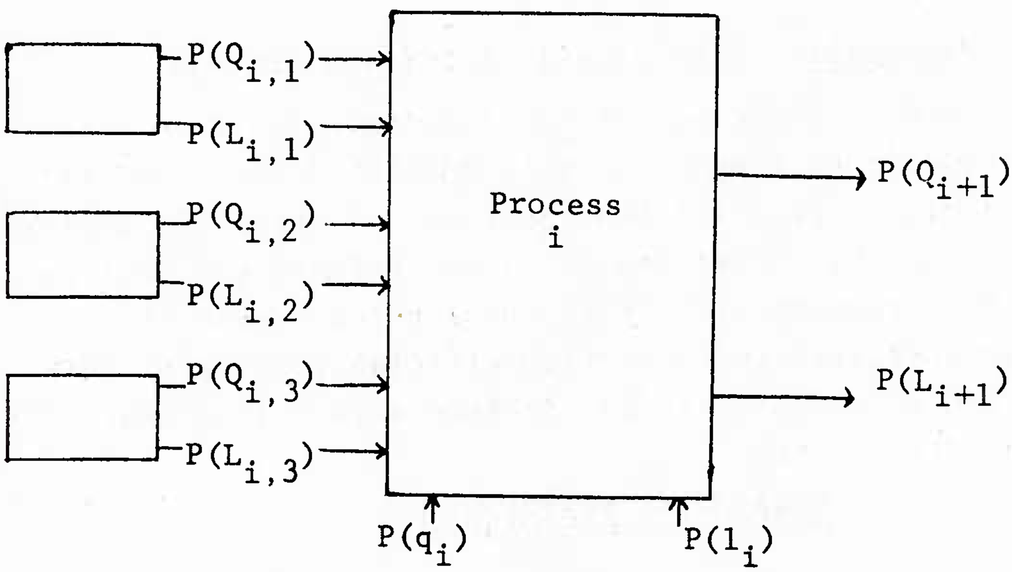
$$P(L_{i+1}) = P(l_i) + \sum_{k=1}^{j} P(L_{i,k}) \tag{3-25}$$

Expressing equations (3-12) and 3-13) in the simplified notation of Section 3.1.2.

$$Q_{i+1} = q_i + \sum_{k=1}^{j} Q_{i,k} \tag{3-26}$$

$$L_{i+1} = l_i + \sum_{k=1}^{j} L_{i,k} \tag{3-27}$$

<u>Example</u> Consider a manufacturing system that consists of the assembly of three units to form another unit shown as follows.



ASSEMBLY PROCESS EXAMPLE

The incoming and process induced defect probabilities are given by

$$P(Q_{i,1}) = P(Q_{i,2}) = P(Q_{i,3}) = 0.02$$

$$P(L_{i,1}) = P(L_{i,2}) = P(L_{i,3}) = 0.02$$

$$P(q_i) = 0.05$$

$$P(l_i) = 0.05$$

The outgoing defect probabilities computed from equations (3-22) and 3-23) are given below.

$P(Q_{i+1}) = 0.106$

$P(L_{i+1}) = 0.106$

Assuming small values for defect probabilities and using equations (3-24) and 3-25)

$P(Q_{i+1}) = 0.11$

$P(L_{i+1}) = 0.11$

3.1.4 Probability Considerations for Inspections

In an inspection process of a manufacturing system, the basic objective is to find units with quality defects and reject them. It should be recalled from Section 3.2 that only quality defects are found by inspection as latent defects will not be detected. This section will first develop the probability considerations related to inspection efficiency and then show how inspection efficiency can be combined with reject statistics to determine defect rates.

INSPECTION EFFICIENCY

The inspection efficiency is defined as the probability of rejecting a unit, given it has a quality defect. For the sake of explanation, the following events are assumed to be those pertaining to the inspection process.

Q - The unit has a quality defect.

E_I - The unit is inspected (a function of the AQL)

E_D - The inspection device detects a quality defect (this is a function of equipment calibration, equipment capabilities relative to particular defect types, etc.)

E_W - The inspector properly uses the device (this is a function of inspection procedures, inspector experience, time for inspection, etc.)

E - The unit is rejected.

It is assumed that a unit with a quality defect will always be rejected if the events E_I, E_D, and E_W takes place. The events (E_I, E_D, E_W, Q) are assumed independent.

The probability of detecting a quality defect is the inspection efficiency and is given by

$$P(E|Q) = P(E\ E_W E_D E_I|Q) \tag{3-28}$$

or

$$P(E|Q) = P(E_W)P(E_D)P(E_I) \tag{3-29}$$

also note that

$$P(\hat{E}|Q) = 1-P(E|Q) \tag{3-30}$$

The probability that a unit has a quality defect and is rejected as a result of an inspection is given by

$$P(EQ) = P(E|Q)\ P(Q) \tag{3-31}$$

where P(Q) is the probability of the unit having a quality defect. The probability that a unit has a quality defect and is not rejected is

$$P(\hat{E}Q) = P(\hat{E}|Q)\ P(Q) \tag{3-32}$$

<u>Example</u>: An inspection is to be performed and the following probabilities are given:

$P(E_I) = 1.0$

$P(E_D) = 0.9$

$P(E_W) = 0.9$

What is the inspection efficiency?

From equation (3-29) the inspection efficiency can be calculated and is

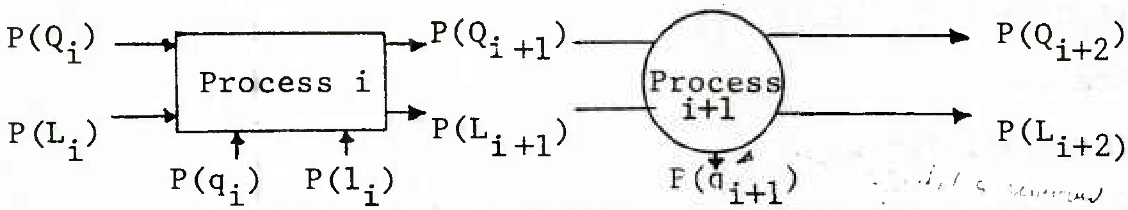
$P(E|Q) = 0.81$

or in the simplified notation of equation (3-5)

$E = 0.81$

DETERMINATION OF DEFECT RATES FROM REJECT RATES

In many cases the only information available for an analysis of the production system is the inspection reject rates and an estimate of the inspection efficiency. This section shows how inspection efficiency can be combined with inspection reject rates to estimate the defect rate induced by a process. Consider the production system show below.



PROBABILITY DIAGRAM FOR FABRICATION AND INSPECTION

The probability of rejecting a unit by inspection in the system shown above is given by

$$P(q_{i+1}) = P(E|Q)\, P(Q_{i+1}) \tag{3-33}$$

Equation (3-33) can be solved for the defect probability $P(Q_{i+1})$, entering the inspection station.

$$P(Q_{i+1}) = \frac{P(q_{i+1})}{P(E|Q)} \tag{3-34}$$

Combining equation (3-34) with equation (3-8) for a fabrication process and solving for the probability $P(q_i)$ of inducing a defect during fabrication gives

$$P(q_i) = \frac{\dfrac{P(q_{i+1})}{P(E|Q)} - P(Q_i)}{1 - P(Q_i)} \tag{3-35}$$

If the defect rates can be assumed small, equation (3-35) reduces to

$$P(q_i) = \frac{P(q_{i+1})}{P(E|Q)} - P(Q_i) \tag{3-36}$$

Using the simplified notation of Section 3.2, equation (3-36) reduces to

$$q_i = \frac{q_{i+1}}{E} - Q_i \qquad (3\text{-}37)$$

$(q_i + Q_i)E = q_{i+1}$

Example: Suppose the following defect probabilities are known

$$P(Q_i) = 0.02$$

$$P(E\,|\,Q) = 0.08 \quad 0.80$$

$$P(q_{i+1}) = 0.02$$

How many defects were introduced during process i?

From equation (3-35) the probability of introducing a defect during process i is

$$P(q_i) = 0.0051$$

Using equation (3-36) (which implies small values for probabilities) gives

$$P(q_i) = 0.005$$

3.1.5 Probability Considerations for Loading

This section will develop the probability considerations necessary to determine the efficiency of converting latent defects into detectable (quality) defects. After or during the load test, an inspection must be performed to reject the defective units. If the inspection is conducted during the load test, the combination of load test and inspection is known as a screen test. For load tests that are designed to produce failure of the unit containing defects, the subsequent inspection will, in general, have a high efficiency.

LOADING EFFICIENCY

The load test efficiency is defined as the probability of converting a latent defect into a quality defect given the unit has a latent defect. The efficiency of a load test will depend on a large number of factors; however, these factors are related to four basic events listed below.

L - The unit has a latent defect.

S_I - The unit is loaded. (This is a function of sample test size).

S_D - The loading device converts the defect. (This is a function of load levels, types of loads, types of latent defects, time of loading test, etc.).

S_W - The operator properly operates the device. (This is a function of operator fatigue, experience, test complexity, time of test, etc.).

S - The latent defects have been converted to quality defects.

It is assumed that a latent defect will always be converted to a quality defect if the events S_I, S_D, and S_W take place. The events (S_I, S_D, S_W, L) are assumed to be independent.

The probability of converting a latent defect into a quality defect (load test efficiency) is given by

$$P(S|L) = P(S\ S_I\ S_D\ S_W|L) \qquad (3\text{-}38)$$

or

$$P(S|L) = P(S_I)P(S_D)P(S_W) \qquad (3\text{-}39)$$

also note

$$P(\hat{S}|L) = 1 - P(S|L) \qquad (3\text{-}40)$$

<u>Example</u>: A load test is to be performed and the following probabilities are given:

$$P(S_I) = 1.0$$
$$P(S_D) = 0.9$$
$$P(S_W) = 0.9$$

What is the load test efficiency?

From equation (3-39), the load test efficiency can be calculated and is

$$P(S|L) = 0.81$$

or in the simplified notation of equation (3-6)

$$S = 0.81$$

SCREEN TEST EFFICIENCY

In some cases a load test will be combined with an inspection; this is then called a screen. An example of this occurs when a unit is loaded and secondary effects are monitored, thus the latent defect becomes detectable during the load test. All latent defects that are converted and detected are rejected, but latent defects that are converted and not detected return to latent defects after the load test.

To compute the screen efficiency the detection event must be combined with the loading event. The resulting probability of removing a latent defect through loading or screen efficiency is given by

$$P(S_S|L) = P(S|L)P(S_E) \tag{3-41}$$

where

S_E - The inspection device detects the defect.

$P(S_E)$ - The inspection efficiency.

S_S - The latent defect is detected.

3.1.6 Derivation of Post Production MTBF.

The following discussion will develop the theoretical background for relating failure rate to defect rate. The objective is to derive an expression to calculate the degradation in MTBF occurring from defects induced by the manufacturing process. The degradation factor will be expressed as a function of the preproduction and post production defect rates.

Let λ_1 represent the preproduction or inherent failure rate of an item. Let λ_2 be the post production failure rate. The time to failure (t) of the item is assumed to be deriveable from two exponential components

$$f_1(t) = \lambda_1 e^{-\lambda_1 t} \tag{3-42}$$

and

$$f_2(t) = \lambda_2 e^{-\lambda_2 t} \tag{3-43}$$

The expected values are:

$$MTBF_1 = \theta_1 = 1/\lambda_1 \tag{3-44}$$

$$MTBF_2 = \theta_2 = 1/\lambda_2 \tag{3-45}$$

Assuming a one to one correspondence between defects and failures, the defect rates as a function of time, may be expressed as the unreliability. Then the defect rates at time t are:

$$P(D_1|t) = 1-e^{-\lambda_1 t} \tag{3-46}$$

$$P(D_2|t) = 1-e^{-\lambda_2 t} \tag{3-47}$$

where

$P(D|t)$ = Probability the item will be defective at time t.

Of particular interest to this analysis are defect rates occurring in the infant mortality period (t_o) shortly after manufacturing

The probability of an inherent defect occurring in time (t_o) is:

$$P(D_1|t_o) = 1-e^{-\lambda_1 t_o}$$

This expression may be expanded in a Taylor series and since (t_o) is small compared to the meantime between failures, approximated as:

$$P(D_1|t_o) \simeq \lambda_1 t_o \tag{3-48}$$

Similarly for the post production defect rate:

$$P(D_2|t_o) \simeq \lambda_2 t_o \tag{3-49}$$

Experience has shown the post production defect rate to exceed the inherent defect rate. Let γ represent the factor of proportionality (the degradation factor).

Then:

$$P(D_1|t_o) = \gamma P(D_2|t_o) \tag{3-50}$$

where

$\gamma > 1$

or from equations (3-48) and (3-49) it may be shown that:

$$\lambda_1 t_o = \gamma\ \lambda_2 t_o \tag{3-51}$$

From equations (3-50) and (3-51)

$$\frac{P(D_1|t_o)}{P(D_2|t_o)} = \gamma = \frac{\lambda_1}{\lambda_2} \tag{3-52}$$

From equations (3-44) and (3-45)

$$\frac{\lambda_1}{\lambda_2} = \frac{MTBF_2}{MTBF_1} \tag{3-53}$$

Then combining equations (3-52) and (3-53)

$$\frac{P(D_1|t_o)}{P(D_2|t_o)} = \frac{MTBF_2}{MTBF_1} \tag{3-54}$$

Theoretical aspects of how defects affect failure densities, hazard rates and reliability are discussed in Appendix A. Equations are developed to analyze the effects of removing quality defects from a unit.

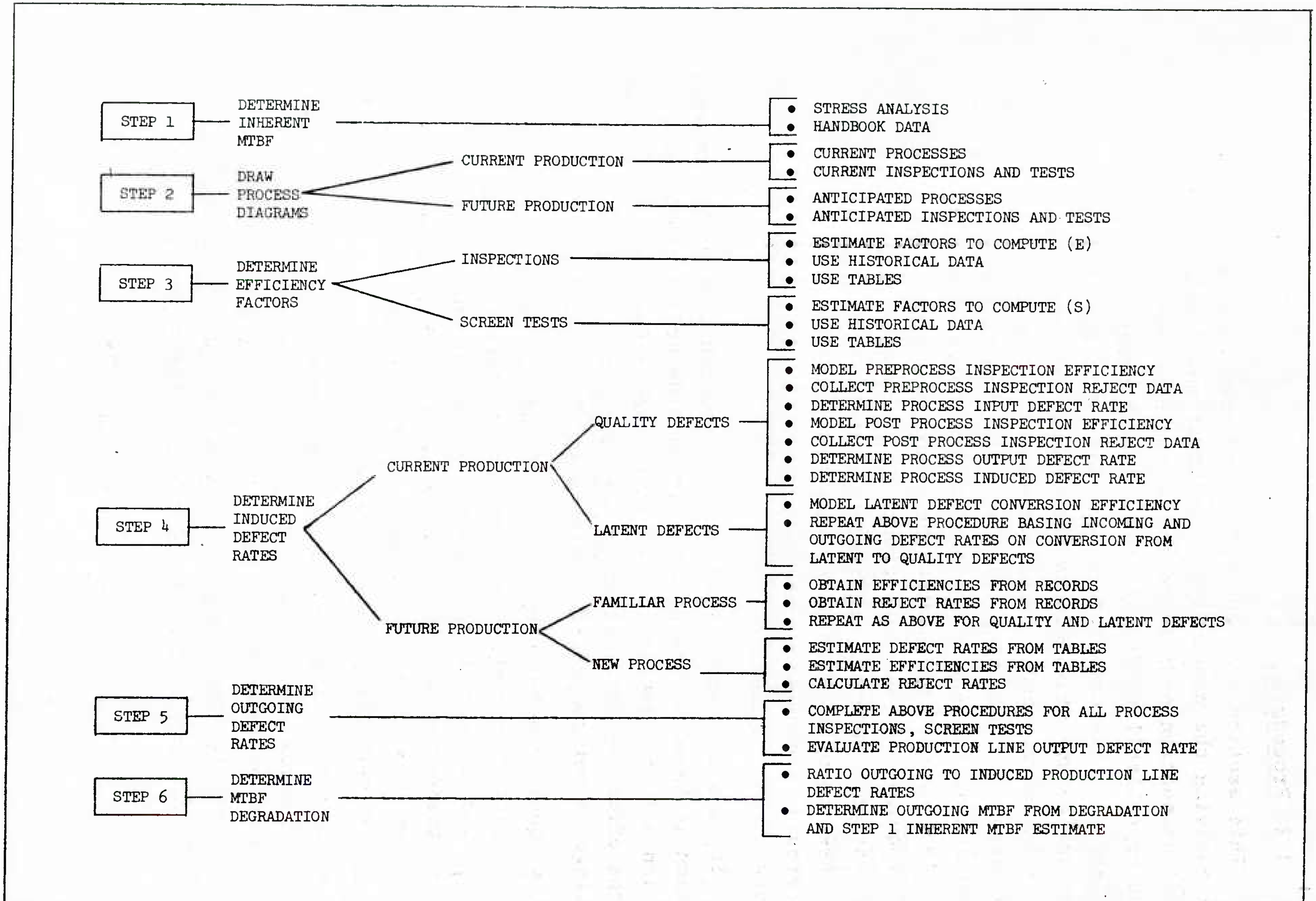
3.2 Procedure

This section provides a detailed step by step procedure for applying the probability considerations developed in the previous section of this report to the assessment of production induced reliability degradation. The procedure, as outlined in Table 3.1 presents a technique for depicting the production flow and determining defects introduced and removed at various steps in the process. Defect rates are followed through the production flow allowing calculation of the number of defects remaining at the end of the production process. A comparison of defect quantities leaving the production process with inherent defect quantities allows estimate of production reliability degradation. Numerics required to exercise the procedure have been compiled into data tables included in Section 3.3 and provide a convenient source of input when measurable values are not available.

It should be emphasized that the procedure described in this section is based on the probability considerations discussed in Section 3.1 of this report. As indicated in Section 3.1, essential to the effective application of the procedure is the ability to distinguish between quality defects and latent defects.

- Quality defects are usually found during initial performance of a component immediately after manufacture and are normally discovered by conventional quality inspection methods or other tests which provide observations of the components' condition and capability for operation at the moment.
- Latent defects are usually discovered after some period of normal operation. (Their discovery requires application of combinations of operating time and stress or sophisticated observation techniques which uncover weaknesses likely to cause failure in future operation).

Table 3-1 PRODUCTION DEGRADATION METHODOLOGY



It also should be noted that the short notation and abbreviated formula described in Section 3.1 and summarized in Table 3-2 is used as the basis for the procedure described in this section.

Table 3-2 NOTATION AND FORMULAE USED IN THE PROCEDURE

NOTATION

L_i	=	Latent defects in a component prior to a process (i)
L_{i+1}	=	Latent defects in a component after a process (i)
Q_i	=	Quality
Q_{i+1}	=	Quality defect in a component after a process (i)
E	=	Inspection efficiency - the probability of detecting a quality defect
S	=	Loading efficiency the probability of converting a latent defect into a detectable defect.

APPLICATION	FORMULAE		
Fabrication Process	1.	$Q_{i+1} = Q_i + q_i$	(3-55)
	2.	$L_{i+1} = L_i + l_i$	(3-56)
Inspection Process	3.	$Q_i+1 = Q_i(1-E)$	(3-57)
	4.	$L_{i+1} = L_i$	(3-58)
Screen Test	5.	$Q_{i+1} = Q_i$	(3-59)
	6.	$L_{i+1} = L_i \; 1-(S)(I)$	(3-60)
Efficiency Modeling	7.	$E = E_W \, E_D \, E_I$	(3-61)
	8.	$S = S_W \, S_D \, S_I$	(3-62)
Manufacturing Degradation Estimate	9.	$\frac{MTBF_{in}}{MTBF_{out}} = \frac{P(D_2 \mid t_o)}{P(D_1 \mid t_o)}$	(3-63)

The reliability evaluation procedure involves six steps as follows:

P. Do. = probability of defects after process
= also the probability of failure after process

Step 1 established the MTBF of the unit as it enters the production process. Input MTBF is assumed to be at the inherent level determined from design analysis.

Step 2 establishes a production process flow diagram and identifies the sequence of fabrication or assembly processes, inspections and screen tests. This diagram may depict either a current or possible future production flow.

Step 3 establishes efficiency factors for inspection and screen tests.

Step 4 defines procedures for selecting quality and latent defect numerics associated with specific production processes. The calculation procedure for a current production process requires collection of reject data to directly calculate the induced defect rates. The procedure for a future process necessitates the use of historical data. A gross data base developed from historical data is provided in Section 3.3 of this report.

Step 5 iterates the mathematical procedure for all production process steps allowing calculation of production line output defect rate.

Step 6 establishes outgoing MTBF from the inherent value and the production degradation factor calculated from the above steps.

In order to perform Step 6, the relationship between defect rate and failure rate must be known. Though an item having a defect is somewhat lacking from a total quality standpoint, it will not necessarily fail. A defect as used in this study is defined as a possible cause of failure because the item (part, component or material) lacks some quality attributes necessary for it to meet its specifications. In order to further clarify the difference between defect rate and failure rate the following comments apply:

(a) Defects can exist in a hardware item but never manifest themselves as failures because the item was not exercised environmentally and functionally to the level which causes failure.

(b) A defect may be a cause of failure, therefore, every failure has at least one associated defect. Note however that the production model, as discussed in Section 3.1, assumes a one to one correspondence exists between defects and failures. This is a useful (worst case) approximation.

(c) A defect can be corrected or eliminated. This has a direct effect on failure rate. Therefore, the approach to reliability or failure rate improvement is to eliminate defects or reduce the probability of defects.

To assure the reliability of helicopter systems or components as they are released to the field requires a reliability growth program during production. This involves successive application of the procedure outlined above as design and process changes and/or improvements are made. Reliability growth during production is described in detail in Section 5.3 of this report. However, to be both effective and practical, the control and growth program can only be applied to those components which have the maximum impact on unreliability. Subsequently, prior to performing the production reliability analysis procedure, those parts most critical to unreliability and/or reliability degradation should first be identified.

A commonly applied procedure in a well structured R&M program is failure mode analysis. This technique involves determining what parts in a system or component item can fail and their modes of failure. The application of failure mode analysis to the investigation of field failures provides a method to pinpoint key areas for concentrating quality, inspection and manufacturing process controls.

Fault tree analysis is a particular approach to identifying failure modes. Using this approach, a highly detailed logic diagram is structured depicting basic causes of field failures.

The association of probabilities to these causes, as may be obtained from field failure numerics, allows a criticality to be calculated, relating the probability of some overall failure to the basic cause. Ranking of these criticalities allows a comparison of production induced failure modes with design and field induced failure modes (due to operation and maintenance). A detailed matrix is generally formulated providing a tabulation of basic faults, their occurrance probabilities and criticalities, and suggested changes. A convenient format for such an analysis is shown in Figure 3-1. From the matrix, production induced failure modes making significant contributions to field failures may be identified and manufactured items responsible for failures isolated. Full details relating to the performance of failure mode analysis is described in AVSCOM's Reliability and Maintainability Handbook.[1]

The application of failure mode analysis allows selection of a limited number of items for which a detailed control and growth program would be most effective. A concentrated effort to promote reliability growth of these items in production will positively impact field reliability. The identification of those production processes whose improvement would most effectively reduce production degradation is readily implemented by the step by step procedure outlined above and as described in the following paragraphs.

The details involved in the implementation of each of the above steps are described in the following paragraphs. Gross data required in the calculations may be selected from Section 3.3 when more accurate numerics are not available.

FAILURE MODE AND EFFECTS ANALYSIS

Date 1/5/76 ENGINEER R.A.M. Page 1 of 1

HELICOPTER UTTAS SUBSYSTEM Main Transmission

PART	FSN	FAILURE MODE	FAILURE EFFECT	FAILURE FREQUENCY	CRITICALITY	RECOMMENDATION
Roller Bearing	1765-703-XXX	Burr on roller	Frozen bearing	.0000X	XXXX	1) Improve tumble deburr operation 2) Improve roughness inspection efficiency
Gear	1829-701-XXX	Flaw in gear	Broken gear	.00000X	XXXX	1) Improve casting process 2) Increase inspection efficiency

Figure 3-1 FAULT TREE MATRIX

Step 1 - Determine Inherent MTBF

The initial step in the procedure is to establish the MTBF prior to production. This value may be calculated using stress analysis technques which allow prediction of MTBF as a function of stress/strength distributions as depicted below in Figure 3-2.

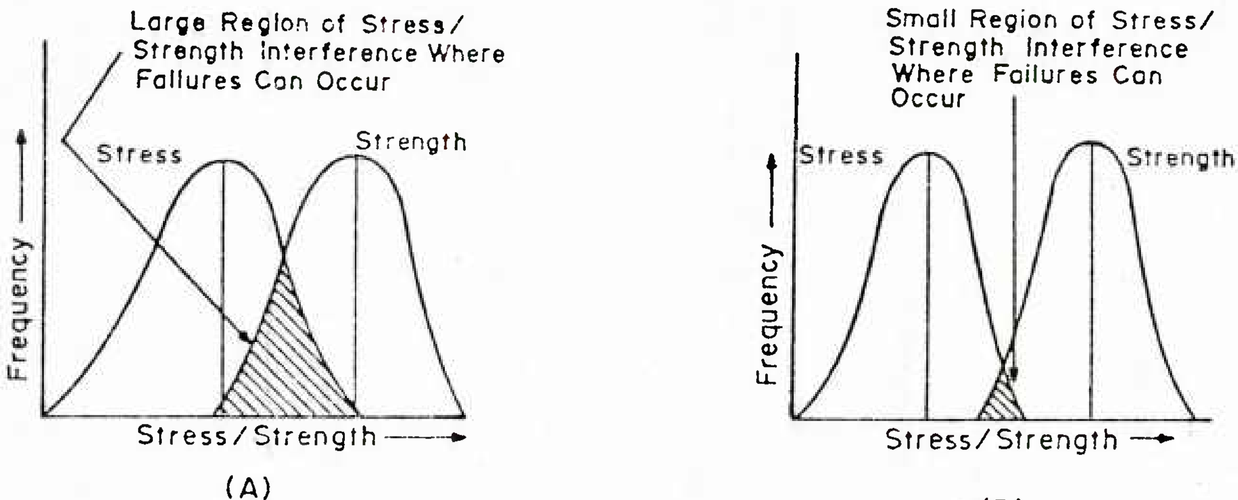


Figure 3-2 REGION OF STRESS/STRENGTH INTERFERENCE WHERE FAILURES CAN OCCUR

Probabilistic design analysis may be applied to assess failure densities as a function of the interaction between unit stress and strength distributions. Application of this technique allows the assessment of inherent MTBF in terms of the interaction between stresses such as fatigue, thermal expansion, creep, corrosion and embrittlement and part strengths which inhibit failure in the presence of these stresses.

When detailed data allowing the performance of probabilistic design analysis is not available to the analyst, less precise estimates of inherent MTBF may be achieved through use of historical data. Tabulations of such data may be found in sources such as the RADC Non-Electronic Reliability Notebook.[8] To facilitate the application of the production degradation model, Table 3-3 is presented in Section 3.3. The intent of Table 3-3 is not to present an all inclusive tabulation of component MTBF's but to provide a summary for a variety of parts common to many helicopter systems. The data presented in these tables is qualified to provide gross estimates only and should in no way be construed to provide predictions of the accuracy achieved through rigorous design analysis.

A review of the available techniques for estimating a unit's inherent MTBF can be found in AVSCOM's "Reliability and Maintainability Handbook".[1]

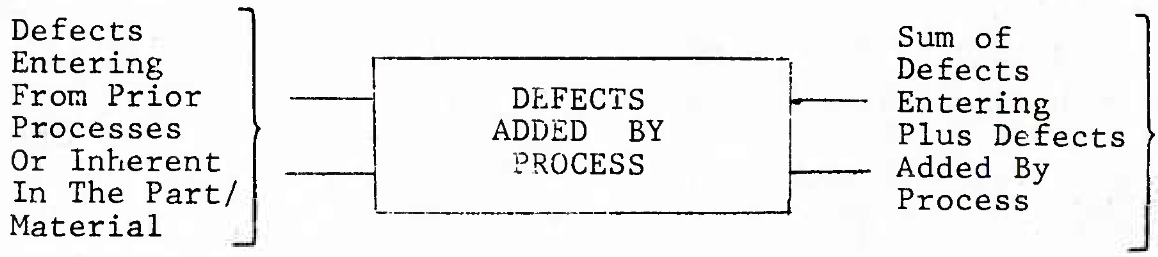
Step 2 - Structure Process Diagrams

Refering to Table 3-1, the next step in the procedure requires the structuring of a diagram depicting the overall manufacturing operation. An option of two procedures is indicated depending on whether a current or anticipated helicopter manufacturing operation is being analyzed. Current production allows accurate structuring of the process diagram based on observation of the manufacturing operation. Future production requires judgements of anticipated processes, inspections and tests, as well as their sequence when structuring the process diagram. The technique for structuring the diagram for a current or future process is discussed below.

a. Current On-going Production Process

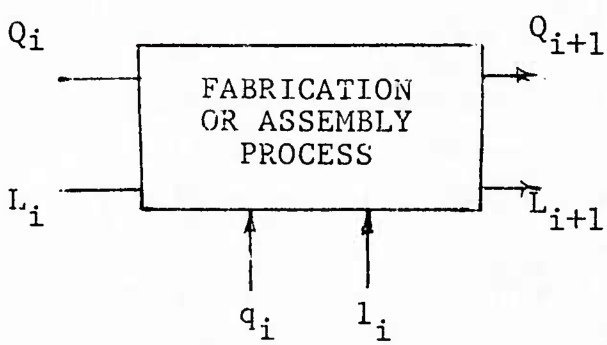
Draw diagrams showing all production processes based on the sequence of operations beginning with reception of purchased parts or raw materials and ending with final assembly and test of the unit prior to shipment. The diagrams should include all machining processes, build-up of subassemblies, inspection processes, load tests and screening tests occuring in production of the unit. Figures 3-3, 3-4, and 3-5 show the symbols, notational conventions and equations used during these analyses for a fabrication process, an inspection process or a stress test. In cases where large, complex components are being analyzed, it may be necessary to prepare preliminary production flow diagrams to aid in identifying all activities incident to the manufacture of the unit. This is especially true where numerous subassemblies or parts are fabricated outside the main production flow.

CONCEPTUALLY



A FABRICATION PROCESS ADDS DEFECTS

SYMBOLICALLY



$$Q_{i+1} = Q_i + q_i$$

$$L_{i+1} = L_i + l_i$$

where

Q_i = Quality defects in a part prior to process i

Q_{i+1} = Quality defects in a part after process i

L_i = Latent defects in a part prior to process i

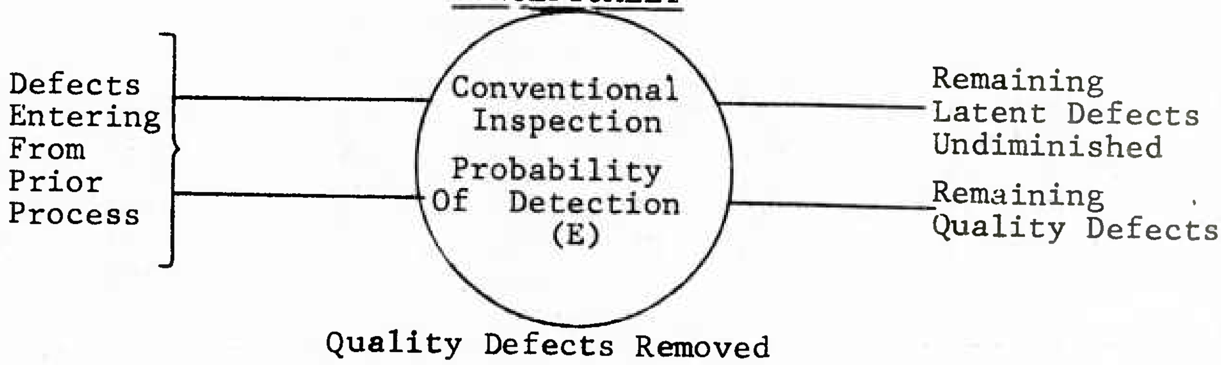
L_{i+1} = Latent defects in a part after process i

q_i = Quality defects induced by process i

l_i = Latent defects induced by process i

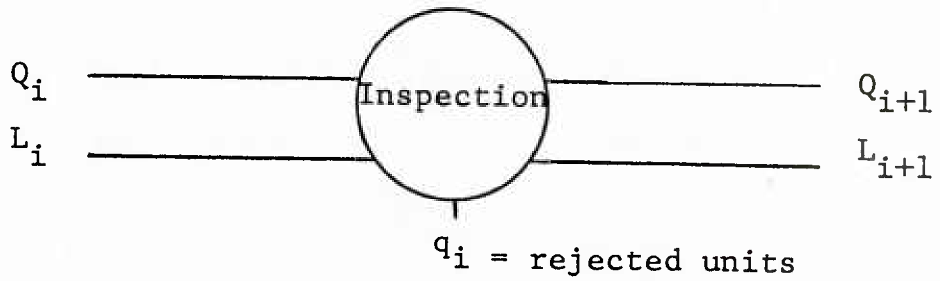
Figure 3-3 SYMBOLS AND EQUATIONS FOR FABRICATION OR ASSEMBLY PROCESSES

CONCEPTUALLY



CONVENTIONAL INSPECTION PROCESS REMOVE ONLY QUALITY DEFECTS

SYMBOLICALLY



$$Q_{i+1} = Q_i\ (1-E) \qquad\qquad q_i = (E)(Q_i)$$

$$L_{i+1} = L_i$$

where:

E = Inspection efficiency

q_i = Quality defect rejected by inspection

Q_i = Quality defect prior to inspection

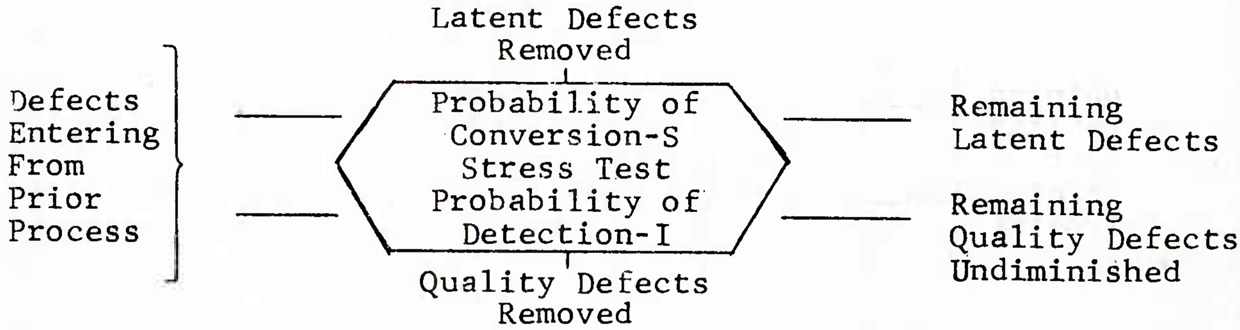
Q_{i+1} = Quality defect after inspection

L_i = Latent defect prior to inspection

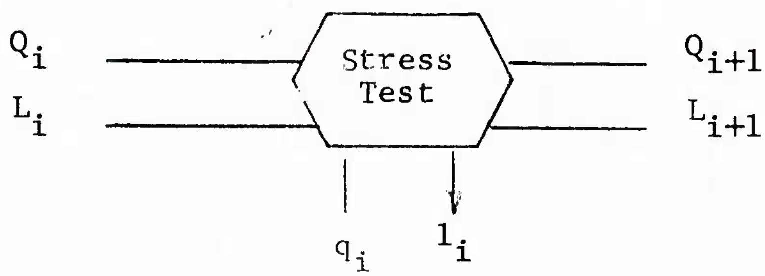
L_{i+1} = Latent defect after inspection

Figure 3-4 SYMBOLS AND EQUATIONS FOR CONVENTIONAL INSPECTION PROCESSES

CONCEPTUALLY



SYMBOLICALLY



$Q_{i+1} = Q_i$

$L_{i+1} = L_i - l_1$

$l_i = (S)\ (I)\ (L_i)$

where:

Q_i = quality defects in a part prior to process i

Q_{i+1} = quality defects in a part after process i

L_i = latent defect in a part prior to process i

L_{i+1} = latent defect in a part after process i

l_i = latent defect converted to quality defect

S = load test efficiency

Figure 3-5 SYMBOLS AND EQUATIONS FOR STRESS TESTS

b. Future Production

Production flow diagrams of similar familiar processes, when available, may provide models for structuring future production flow diagrams. The symbols, notational conventions and equations depicted in Figures 3-3 , 3-4 , and 3-5 shall be used to define future production processes.

Often, the anticipated manufacturing operation is an updated or improved version of a current production process. In evaluating the anticipated operation, the process flow diagram must be accurately revised to reflect any process alterations, additions or changes of sequence. Alterations of the process flow necessitates recalculation beginning at the start of the production flow.

Step 3 - Determine Efficiency Factors

Table 3-1 identifies three methods of determining efficiencies for inspections and screen tests. A single efficiency estimate is required for inspections, while evaluation of screen tests require estimates of the efficiency with which latent defects are converted to quality defects and an estimate of the efficiency with which the converted defects are detected.

Efficiency factors should be based on past experience for the same or a similar process when such data exists. For newly instituted or proposed inspection and load test operations having little or no prior history as to how many defects are found, estimates of inspection and test efficiency must be made. Methods for estimating efficiency factors are described in the following paragraph.

a. Inspection Efficiency

Table 3-4 in Section 3.3 provides ranges of expected efficiency factors for various inspection techniques. The efficiency of an inspection depends on all factors involved in or related to the inspection. The inspection should be assessed and characterized in a report form. The inspections should be characterized relative to complexity, efficiency of inspectors, inspection equipment and tools, and past experience with similar inspections. Figure 3-6 provides a sample of a report form allowing assignment of weight factors to inspection efficiency assessment parameters. To illustrate an efficiency estimate, the report form (as shown in Figure 3-6) has been completed with sample data to identify descriptive parameters, characterizations and weighting factors as may be recorded for an inspection performed after a milling operation. The assessment method presented uses a scale of 100 points which is subdivided relative to contribution and importance of the descriptive parameter in achieving optimum inspection efficiency. The efficiency weight factor is the sum of the assessed weight factors. This efficiency weight factor is substituted into the following formula to approximate inspector efficiency.

$$E = E_L + \frac{W(E_u - E_L)}{100} \tag{3-64}$$

where

E_L = the lower bound of efficiency shown in Table 3-3

E_u = the upper bound of efficiency shown in Table 3-3.

Shown in Figure 3-6 is an assessed weight factor of 80. Based on an upper bound (E_u = 0.9) and a lower bound (E_L = 0.4) found in Table 3-4 for a visual inspection, the inspection efficiency is E = 0.8. The above illustration is meant to demonstrate the technique and is not intended to represent an actual value relative to a visual inspection for a milling operation. An actual value, as previously stated, can only be obtained through detailed analysis and evaluation of the inspection using the technique described here.

INSPECTION STATION NUMBER XX

Descriptive Parameter	Characterization	Optimum Weight Factor	Assessed Weight Factor
1. Complexity of Item Under Test	Simple part, easy access to measurement	20	20
2. Measurement Equipment	Micrometer for dimensional check, visual for surface finish	15	10
3. Inspector Experience	Highly qualified, 16 years in quality control	25	20
4. Time for Inspection	Production rate allows adequate time for high efficiency	15	10
5. Sampling Plan	All parts are inspected	25	20

Efficiency Weight Factor: $W = 80$

$$E = E_L + \frac{W(E_U - E_L)}{100}$$

Figure 3-6 INSPECTION EFFICIENCY REPORT FORM (With Sample Data)

b. Load Test Efficiency

Load tests are designed to apply stress to units while in the factory with objective of converting latent defects to quality defects (i.e., a quality defect is a detectable defect). The efficiency of a load test depends on all factors involved or related to the test. Table 3-5 in Section 3.3 provides efficiency estimates for some typical load tests. The test should be assessed and characterized in a manner which will allow engineering judgment to be made as to the efficiency of converting latent defects to quality defects. These characterizations should be made relative to the defect type, test type, similar tests, sample size (for destructive tests) and experience with similar tests. Figure 3-7 shows a sample of a report form which may be used to characterize and assess load tests. To illustrate the type of information recorded on the form, samples of descriptive parameters, characterizations, and weight factors have been provided for a bending test on a link in the flight control linkage.

Weight factors are assigned as for assessment of inspection efficiencies. The assessment method uses a scale of 100 points which is subdivided relative to contribution and importance of the descriptive parameter in achieving optimum conversion efficiency. The efficiency weight factor is the sum of the assessed weight factors.

The efficiency weight factor is substituted into the following formula.

$$S = S_L + \frac{W(S_U - S_L)}{100} \qquad (3\text{-}65)$$

where

S_L = the lower bound of efficiency shown in Table 3-5

S_U = the upper bound of efficiency shown in Table 3-5

LOAD TEST NUMBER XX			
Descriptive Parameter	Characterization	Optimum Weight Factor	Assessed Weight Factor
1. Stress Inducing Equipment	Within normal operating range of equipment	10	10
2. Bending Test Plan	1,2 times, expected peak load	20	10
3. Defects to be Detected	• voids • inclusions • cracks • surface flaws	20	20
4. Detection Instrumentation	Ultrasonic echo	20	20
5. Inspection Experience	Highly qualified, 25 years in quality control	30	30

Conversion Efficiency Weight Factor: W = 90

$$S = S_L + \frac{W(S_U - S_L)}{100}$$

Figure 3-7 LOAD TEST REPORT FORM

Shown in Figure 3-7 is an assessed weight factor of 90. Based on an upper bound (E_U = .97) and a lower bound (E_L = .60) found in Table 3-5 for compressive tensile tests, the conversion efficiency is E = 0.9. The above illustration is meant to demonstrate a technique and is not intended to provide an actual value for bending test conversion efficiency. The actual value, as previously stated, can only be determined through detailed analyses and evaluation of the test.

Step 4 - Determine Induced Defect Rates

p 58

Table 3-1 identifies two basic techniques of determining induced defect rates:

(a) For a current production process, induced quality or latent defects may be calculated if a process is bounded by inspection stations or test stations. If the efficiencies of the test or inspection stations are known and the station reject rates are measured, the defects entering and leaving the process may be determined. The difference between the entering and leaving defect rates is the induced defect rate.

(b) The technique for assessing future production process defect rates may be based on a familiar process or a new process. If a familiar process, historical records of efficiencies and defect rates provide input to the above calculational procedure.

If a new process, induced defect rates may be obtained from data based on process repeatability, as that tabulated in Tables 3-6, 3-7, and 3-8, presented in Section 3-3. In addition to direct application of the data to degradation analysis, it may be applied to calculations of inspection and test station reject numerics.

The techniques applicable to determining defects induced by current and future production processes are discussed in greater detail below.

a. Current Production

Calculation of the induced quality and latent defect rate may be achieved if inspection efficiencies and reject rates are known for quality control stations and test stations prior to and after the process to be assessed. If several processes occur between inspections, the total defect rate for all processes results. Performance of the calculations are facilitated by the example illustrated in Figures 3-8 and 3-9. The steps taken are as follows:

Quality Defects

1. Establish the efficiency of the preprocess inspection (from Step 2).
2. Collect preprocess inspection reject data.
3. Calculate input defect rate to the process. It may be shown from Eqs. (3-55) and (3-57) presented in Table 3-2, that:

$$Q_{in} = q_1 \left(\frac{1 - E_1}{E_1} \right) \tag{3-66}$$

where:

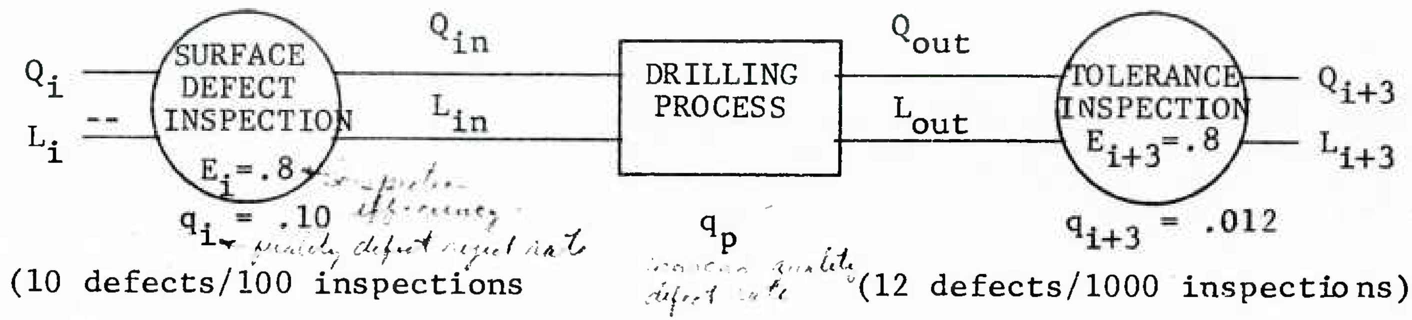
Q_{in} = input quality defect rate to the process

q_1 = quality defect reject rate of the preprocess inspection

E_1 = preprocess inspection efficiency.

4. Establish efficiency of the post process inspection (from Step 2).
5. Collect post process inspection reject data.
6. Calculate post process output quality defect rate. It may be shown from Eq. (3-57) presented in Table 3-2 that:

$$Q_{out} = \frac{q_2}{E_2} \tag{3-67}$$



$$Q_{in} = q_i \frac{1-E_i}{E_i} = .02 \frac{1-.8}{.8} = .005$$

$$Q_{out} = \frac{q_{i+3}}{E_{i+3}} = \frac{.012}{.8} = .015$$

$$q_P = Q_{out} - Q_{in} = .015 - .005 = .010$$

(10 defects induced/1000 inspections)

EXAMPLE: The Fabrication of a Link in the Flight Control Subsystem.

The link is fabricated from raw aluminum stock and is milled to shape. It is then inspected visually for surface defects. Next it is drilled and the hole tolerance measured. The above calculation illustrates the technique of estimating defects introduced between inspection stations. In the above example, the number of quality defects introduced in the drilling process is determined.

Figure 3-8 DETERMINATION OF PROCESS INDUCED QUALITY DEFECTS

where

Q_{out} = output quality defect rate from the process

q_2 = quality defect reject rate from the post process inspection

E_2 = post process inspection efficiency.

7. Calculate process induced quality defect rate (q_p).

Induced [illegible]

$$q_p = Q_{out} - Q_{in}. \qquad (3\text{-}68)$$

<u>Latent Defects</u> (see Figure 3-9)

1. Establish conversion efficiency of the preload test (from Step 2).
2. Collect preprocess load test reject data.
3. Calculate input latent defect rate to the process. It may be shown from Eqs. (3-56) and (3-60) presented in Table 3-2 that:

$$L_{in} = \ell_1 \frac{1 - (S_1)(I_1)}{(S_1)(I_1)} \qquad (3\text{-}69)$$

where

L_{in} = input latent defect rate to the process

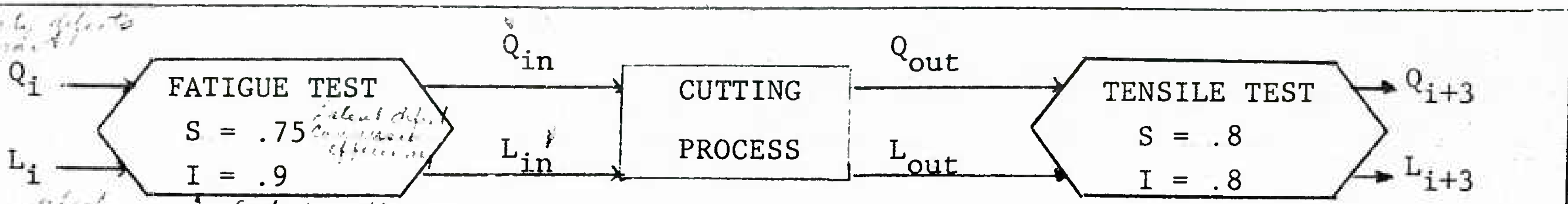
ℓ_1 = latent defect reject rate of the pre-process inspection

S_1 = latent defect preprocess conversion efficiency

I_1 = preprocess detection efficiency.

4. Establish efficiency of the post load test inspection (from Step 2).
5. Collect post process load test reject data.
6. Calculate post process output latent defect rate. It may be shown from Eq. (3-60) presented in Table 3-2 that

$$L_{out} = \frac{\ell_2}{(S_2)(I_2)} \qquad (3\text{-}70)$$



$\ell_i = .24$
(24 defects/100 tests)

$\ell - q$

$\ell_{i+3} = .14$
(14 defects/100 tests)

$$L_{in} = \ell_i \; \frac{1-(S_i)(I_i)}{(S_i)(I_i)} = .24 \; \frac{1-(.75)(.9)}{(.75)(.9)} = .115$$

$$L_{out} = \frac{q_{i+3}}{(S_{i+3})(I_{i+3})} = \frac{.14}{(.8)(.8)} = .215$$

$$\ell_p = L_{out} - L_{in} = .215 - .115 = .100$$

EXAMPLE: The fabrication of a link in the flight control subsystem.

After a drilling process and tolearnace investigation, the link is subjected to a fatigue test. It is then cut and subjected to a tensil test. The above calculation illustrates the technique of estimating defects introduced between test stations. In the above example, the number of latent defects introduced in the cutting process is determined.

Figure 3-9 DETERMINATION OF PROCESS INDUCED LATENT DEFECTS

where

L_{out} = output latent defect rate from the process

ℓ_2 = latent defect reject rate of the post process inspection

S_2 = latent defect post process conversion efficiency

I_2 = post process detection efficiency.

7. Calculate process induced latent defect rate (ℓ_p):

$$\ell_p = L_{out} - L_{in} \tag{3-71}$$

b. Future Production

In assessing induced defect rates for future production, reject data may or may not be available, depending upon whether the future processes are comparable to those experienced in the past. For comparable processes, historical data is preferred to that available through handbooks or other gross tabulations.

For those cases in which gross tabulations must be resorted to, tables of defect rates have been compiled and are included in Section 3.3. Selection of defect rates from the tables requires identifying the manufacturing level of the process. Tables are included for primary processes in which shapes are formed from raw materials (Table 3-6), secondary processes in which finished parts are fabricated (Table 3-7), and tertiary processes in which finished parts are assembled into an end item (Table 3-8). The process should be assessed and characterized in a manner which will allow judgment of the degree to which defect concentration may be increased by the process. This requires for each process or assembly identified on the diagram, an estimate of the percent of defects caused or induced by the process itself or by the personnel performing the process. Each process should be assessed and characterized in a manner which will allow engineering judgment to be made as to the number of defects induced by the process. These characterizations should be relative to the process complexity, equipment used, experience level of personnel, and overall experience with similar processes. Figure 3-10 depicts a sample of a report form suitable to characterize and assess each process. The report form includes information demonstrating evaluation of a milling operation on a small aluminum link used in the flight control linkage. Provided are assessments of complexity, skill requirements of operators, and other information needed to judge the probable number of defects induced by the process.

Weight factors are assigned to descriptive parameters based on a scale of 100 points which is subdivided relative to contribution and importance of the descriptive parameter in achieving optimum process performance. The process weight factor is the sum of the assessed weight factors. This process weight factor is substituted into the following formula to determine the process induced defect rate,

$$(Q + L) = 100 \frac{P}{W} \qquad (3\text{-}72)$$

where

$(Q + L)$ = process induced defect rate

P = defect probability selected from Tables 3-5, 3-6, and 3-7.

Shown in Figure 3-10 is an assessed weight factor of 0.90. Based on an induced defect rate of $(Q + L = .01)$ for a milling process, found in Table 3-6, the induced defect rate for the example illustrated is 0.011. The above illustration is meant to demonstrate a technique and should not be meant to represent an actual value. As previously stated, an actual value can be determined only through detailed analysis and evaluation of the process.

FABRICATION PROCESS STATION NUMBER XXX

Descriptive Parameter	Characterization	Optimum Weight Factor	Assessed Weight Factor
1. Production Process	Simple machining operation on raw aluminum stock	.20	.16
2. Machinist Experience and Training	Experienced machinist recently trained in use of milling machinery	.20	.20
3. History of Similar Parts Production	Have produced similar parts with very few rejects	.10	.10
4. Production Rate	Production rate allows adequate time for part to be made properly	.20	.18
5. Number of Steps in Operation	Mill both sides of link	.10	.08
6. End Item Complexity	Very simple shape	.20	.18

Fabrication Process Weight Factor: W = .90

$$(Q+L) = \frac{P}{W}$$

Figure 3-10 FABRICATION PROCESS REPORT FORM

Calculation of Reject Numerics

The selection of defect rates for a process or series of processes between two inspection or screen stations, allows the calculation of the reject rate from one station, if the reject rate of the other station and the efficiencies are known. Performance of the calculation is facilitated by the example illustrated in Figure 3-11. The steps taken are as follows.

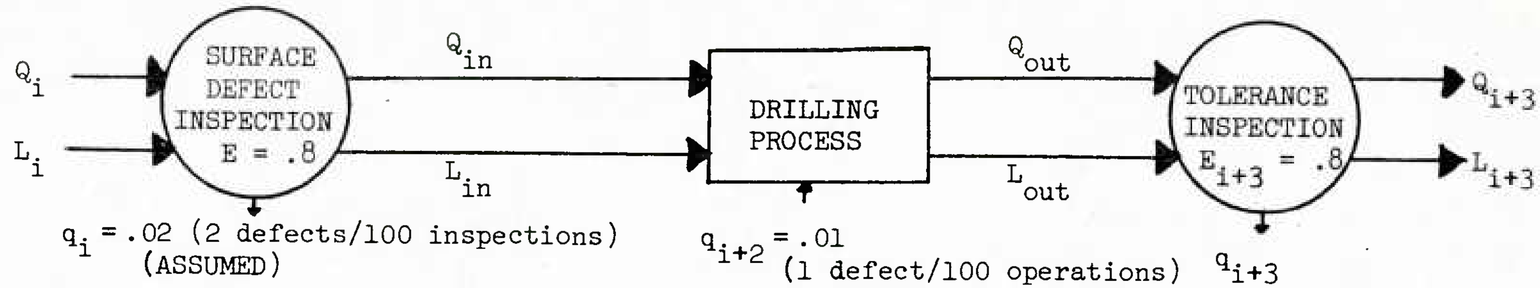
Inspection Stations

1. Establish the efficiencies of both inspection stations (from Step 2).
2. Select the process defect rate from Tables 3-6, 3-7, or 3-8.
3. Estimate the reject rate of one inspection station.
4. Calculate the reject rate of the other inspection station.
   a) If the reject rate of the preprocess inspection is estimated, the reject rate of the post process inspection can be determined from the following relationship derived from Eqs. (3-55) and (3-56) shown in Table 3-2:

$$q_{i+3} = \left(\frac{q_1}{E_1} - q_i + q_{i+2}\right) E_{i+3} \qquad (3\text{-}73)$$

   b) If the reject rate of the post process inspection is estimated, the reject rate of the preprocess inspection can be determined from the following relationship (also derived from Eqs. (3-55) and (3-57) presented in Table 3-2):

$$q_i = \left[\frac{q_{i+3}}{E_{i+3}} - q_{i+2}\right] \div \left(\frac{1}{E_i} - 1\right) \qquad (3\text{-}74)$$

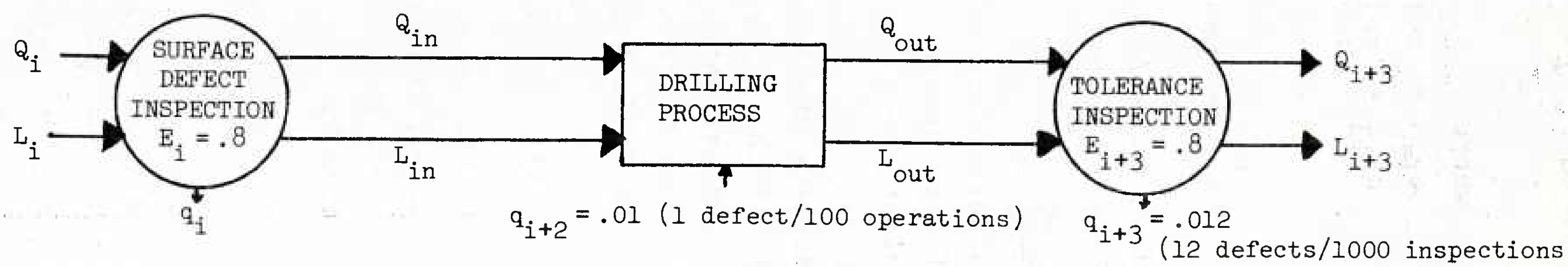


$$q_{i+3} = \left(\frac{q_i}{E_i} - q_i + q_{i+2}\right) E_{i+3}$$

$$q_{i+3} = \left(\frac{.02}{.8} - .02 + .01\right) .8 = .012 \text{ (12 defects/1000 inspections)}$$

Example: The fabrication of a link in the flight control subsystem.

The link is fabricated from raw aluminum stock and is milled to shape. It is then inspected visually for surface defects. Next it is drilled and the hole tolerance measured. The calculations determine the reject rates from the inspection processes. The above example assumes the preprocess inspection reject rate is known. The following example assumes the post process inspection reject rate is known.



$$q_i = \left(\frac{q_{i+3}}{E_{i+3}} - q_{i+2}\right) / \left(\frac{1}{E_i} - 1\right)$$

$$q_i = \left(\frac{.012}{.8} - .01\right) / .25 \approx .02 \text{ (2 defects/100 inspections)}$$

Figure 3-11 PREDICTION OF REJECT RATES

where

q_i = reject rate of the preprocess inspection

q_{i+3} = reject rate of the post process inspection

E_i = efficiency of the preprocess inspection

E_{i+3} = efficiency of the post process inspection

q_{i+2} = process induced defect rate.

A similar analysis can be pursued to calculate reject rates from screen tests. The steps taken are as follows:

<u>Screen Tests</u>

1. Establish the conversion and inspection efficiency of both stations (from Step 2).
2. Select the process defect rate from Table 3-6, 3-7, or 3-8.
3. Estimate the reject rate of one test station.
   a) If the reject rate of the preprocess test station is estimated, the reject rate of the post process test station (from Eqs. (3-56) and (3-60) presented in Table 3-2) is given by:

$$\ell_{i+3} = \left(\frac{\ell_1}{S_1 I_1} - \ell_i + \ell_{i+2}\right) S_{i+3}\, I_{i+3} \qquad (3\text{-}75)$$

   b) If the reject rate of the post process is estimated, reject rate of the preprocess can be determined from the following relationship (derived from Eqs. (3-56) and (3-60) presented in Table 3-2):

$$\ell_i = \left[\frac{\ell_{i+3}}{(S_{i+3})(I_{i+3})} - \ell_{i+2}\right] \div \left(\frac{1}{S_i I_i} - 1\right) \qquad (3\text{-}76)$$

where

q_i = reject rate of the preprocess inspection

q_{i+2} = process induced defect rate

q_{i+3} = reject rate of the post process inspection

S_i = latent defect preprocess conversion efficiency

S_{i+3} = latent defect post process conversion efficiency

I_i = preprocess detection efficiency

I_{i+3} = post process detection efficiency.

Step 5 - Determine Outgoing Defect Rates

With the completion of Step 4, the defects introduced by each production process are known, efficiency factors of each inspection and load test are known, the reject rates are known. This information can be combined to determine the defect rate of an item leaving production. A sample form for tracking defects introduced and removed during the production flow is shown in Figure 3-12. The form includes information demonstrating application to a flight control system link fabrication. The calculational procedure for providing input to Figure 3-12 is as follows.

1. For each fabrication process, add the defects induced by the process,

$$Q_{i+1} = Q_i + q_{i+1} \tag{3-77}$$

$$L_{i+1} = L_i + \ell_{i+1} \tag{3-78}$$

2. For each inspection process subtract the quality defects removed,

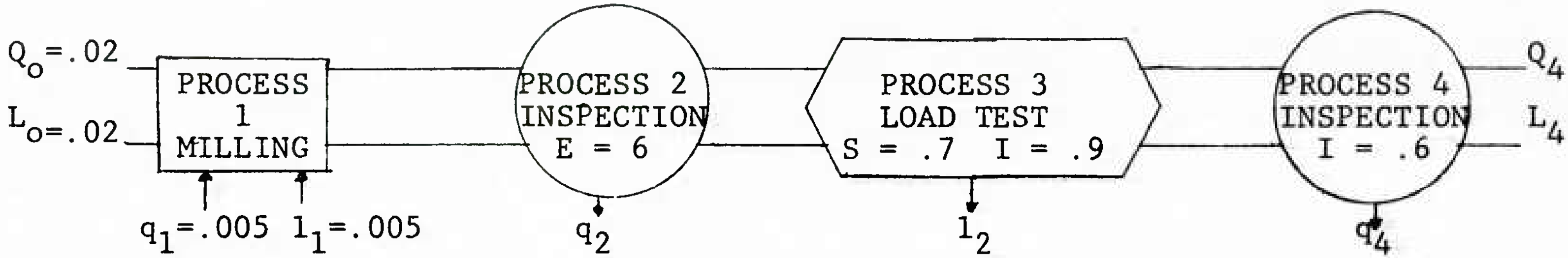
$$Q_{i+1} = Q_i(1 - E) \tag{3-79}$$

3. For each load test subtract the latent defects converted and detected by the test and inspection,

$$L_{i+1} = L_i\left[1 - (S_i)(I_i)\right] \tag{3-80}$$

Step 6 - Determine MTBF Degradation

Determination of outgoing MTBF was theoretically treated in Section 3.1.6. Based on the relationships developed in Section 3.1.6, production reliability degradation was defined as the ratio of inherent defect rate to defect rate remaining



PROCESS DESCRIPTION	DEFECTS PRESENT IN ITEM		DEFECTS INDUCED BY FABRICATION		DEFECTS REMOVED BY INSPECTION	DEFECTS REMOVED BY SCREEN TEST
	Quality Q	Latent L	Quality q	Latent l	Quality q	Latent l
RECEIVING	.02	.02	——	——	——	——
1 MILLING	.02	.02	.005	.005	——	——
2 INSPECTION VISUAL/ DIMENSION	.025	.025	——	——	.015	——
3 LOAD TEST BENDING	.01	.025	——	——	——	.002
4 INSPECTION VISUAL	.01	.023	——	——	.006	——
5	.004	.023				
6						

Figure 3-12 CALCULATION OF TOTAL DEFECT RATE

at the end of production. In terms of variables obtained through application of the preceeding five steps, the degradation factor is:

$$\gamma = \frac{(MTBF)_{in}}{(MTBF)_{out}} = \frac{D_{out}}{D_{in}} \qquad (3\text{-}81)$$

where

γ	=	the degradation factor
$(MTBF)_{in}$	=	mean time between failure prior to production
$(MTBF)_{out}$	=	mean time between failure after production
D_{in}	=	inherent defect rate
D_{out}	=	post production defect rate.

The post production defect rate is determined during Step 5. The inherent defect rate is derived in terms of inherent unreliability. Assuming an exponential failure distribution and a one-to-one correspondence between failures and defects:

$$D_{in} = 1 - e^{-\lambda_{in} t} \qquad (3\text{-}82)$$

where

λ_{in} = inherent failure rate $(1/MTBF)_{in}$.

The inherent failure rate may be decomposed into an operational and a nonoperational component. Then the inherent failure rate may be expressed as

$$\lambda_{in} = \lambda_{op} \left| d + (1 - d)k \right| \qquad (3\text{-}83)$$

where

λ_{op}	=	operational failure rate
d	=	ratio of operational time to total time
k	=	failure rate reduction factor for nonoperational time.

Assuming the factor k is assigned a value of 0.01 based on studies previously conducted by the military and the factor d is assigned a value of 0.0192 based on an average of 168 accumulated helicopter flight hours for a one year period (peacetime), the expression for inherent defect rate then becomes:

based on [illegible] hours = T

$$D_{in} = 1 - e^{-254\lambda_{op}} \qquad (3\text{-}84)$$

The production degraded output MTBF may under these conditions be expressed as:

$$(MTBF)_{out} = (MTBF)_{in} \frac{D_{in}}{D_{out}} \qquad (3\text{-}85)$$

3.3 Data Base

The following tables provide MTBF, defect rate and inspection efficiency data which can be used to implement the procedure described in Section 3.2. This data is intended to be used only when current production statistics or historical data on similar processes is not available. The data presented in these tables was derived from compiled experience of production engineers representing a variety of helicopter component and system manufacturers. The objective was to provide a data base broad enough to cover all applications of helicopter fabrication and assembly. Reliability estimates computed via this data, by nature of its general applicability, should not be considered to have a high degree of accuracy. The value of this data is that it does suffice to provide consistent estimates of production reliability degradation during early planning phases and as such provides a suitable basis for pre-production process/inspection cost trade-off studies. As an item moves into production the actual production line data, as it becomes available, should be used in place of the data tabulated in this report to provide more accurate reliability estimates, to identify those processes in need of improvement and, in general, provide a viable means to control production reliability.

The following tables are presented preceded by a brief discussion of the data source and the rationale for application to the production reliability degradation model.

Table 3-3 - Inherent MTBF
Table 3-4 - Inspection Efficiency
Table 3-5 - Load Test Efficiency
Table 3-6 - Defect Rates for Primary Fabrication Processes
Table 3-7 - Defect Rates for Secondary Fabrication Processes
Table 3-8 - Defect Rates for Tertiary Fabrication Processes

INHERENT MTBF (Table 3-3)

The following table lists MTBF's for typical helicopter components. The estimates recorded in the table are based on data obtained from the RADC Nonelectronic Reliability Notebook[8] and are repeated here for convenience. Data presented therein is general in nature and its application to a particular helicopter can be made only with a limited degree of confidence. Probabilistic design analysis or other standard techniques provide more accurate estimates when time and data permit. When more accurate data does not exist, the following tabulation allows gross estimates of inherent MTBF. As described in Step 1 of the procedure discussed in Section 3.2, these inherent values represent the upper bound of reliability at the starting point for the production analysis.

Table 3-3 INHERENT MTBF

PART TYPE	MTBF (hrs)
ACCUMULATOR	
General	2000.0
Hydraulic	12444.5
ACTUATORS	
Linear, General	1402.9
Linear, Hydraulic	9279.1
Linear, Hydraulic Servo	9317.1
ANTENNAS	
General	8554.8
BATTERIES	
Rechargeable	1477.6
BEARINGS	
General	61820.0
Ball	74638.0
Roller	41666.7
Sleeve	25000.0
Spherical	37577.0
BLOWERS & FANS	
General	11716.7
Axial	10000.0
BRAKES	
General	10000.0
Magnetic	4140.1
CAPACITORS, VARIABLE	
Air	13100.5
Ceramic	106986.2
CIRCUIT PROTECTION DEVICES	
Fuse	5000.0
Circuit Breaker	35000.5
CONNECTORS	
General	97371.0
Coaxial	100000.0
FILTERS, NON-ELECTRIC	
General	502260.2
Liquid	20194.3
Gaseous	38500.0
FITTINGS	
General	33721.1
Quick Disconnect Liquid	3333.3
Hydraulic	257201.6
GASKETS & SEALS	
Gasket	49142.5
O-Ring	3571.4
Seal	21262.2
Packing	170735.9
GYROS	
General	10000.0
Directional	3103.5
Horizontal	700.0
Rate	3923.1
Vertical	3793.1

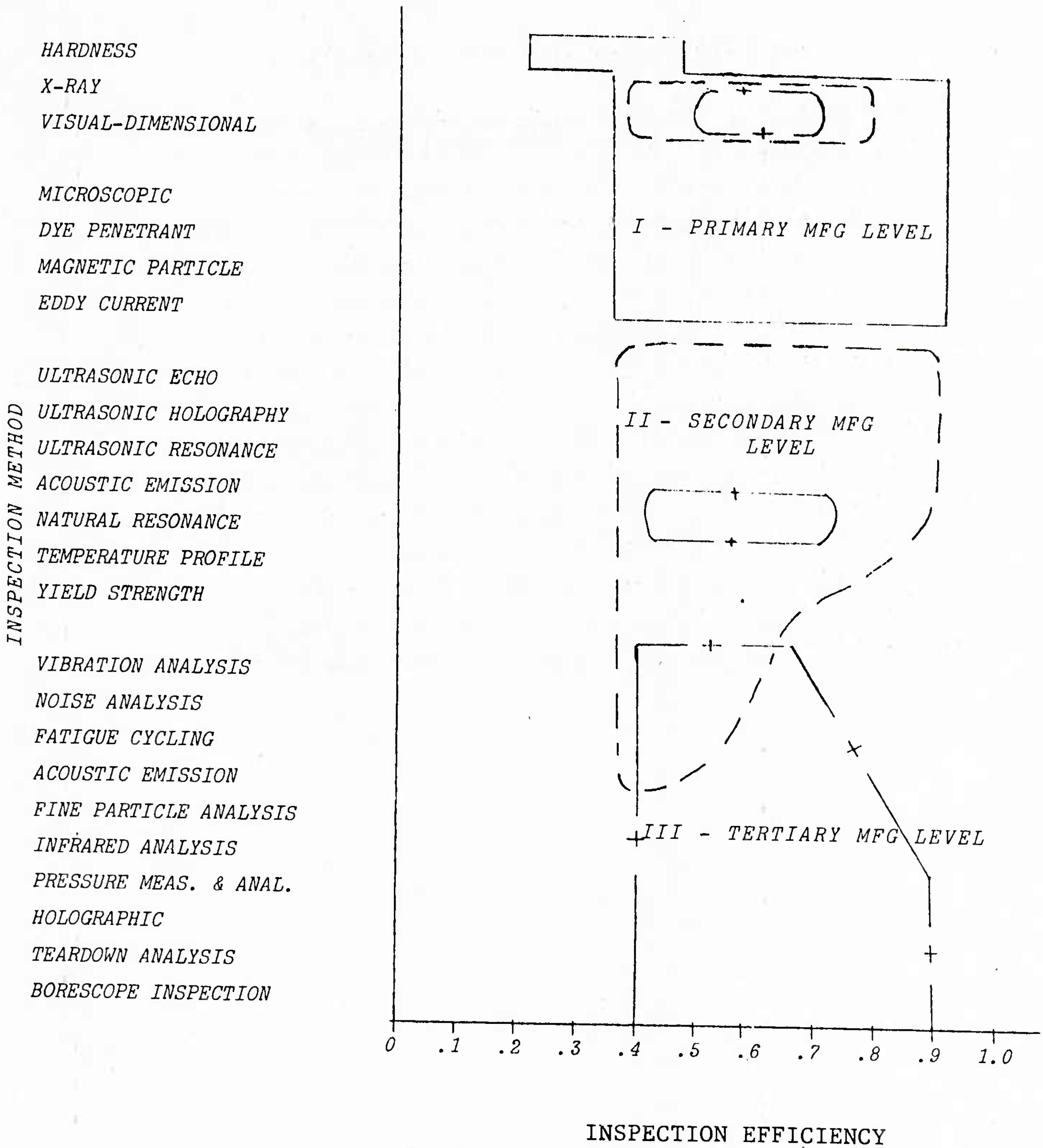
PART TYPE	MTBF (hrs)
HARDWARE	
Bushing	44976.2
Duct	4348.5
Retaining Ring	63532.4
Tail Pipe	425.5
Washer	143163.9
HEATERS, ELECTRICAL	20000.0
HOSES	24971.3
INSTRUMENTS	
Ammeter	5062.5
Compass, General	4450.6
Meter	1166.7
Indicator, General	4462.8
Air Speed	4789.5
Altitude	3709.1
Attitude	2986.4
Bearing Heading	1715.4
Engine Torque	4303.0
Fuel Quantity	9025.5
Slip Turn	5290.5
Tachometer	3700.3
Temperature	7642.9
Vertical Speed	28111.2
MANIFOLDS	13330.8
MECHANISMS, POWER TRANSMITTAL	
Arm	10312.5
Bellcrank	34574.6
Cam	9388.9
Clutch, Friction	1081.5
Coupling	5684.5
Gear	3307.5
MOTORS, ELECTRICAL	
General	5238.1
Hydraulic DC	25499.8
GENERATORS	
General	15513.5
AC	2142.9
DC	4857.1
MOUNTS RESILIENT	3107.7
PUMPS	
Fuel	6288.9
Fuel Boost	5000.0
Hydraulic	2735.6
Hydraulic, Variable Delivery	6014.3
Oil Boost	21999.8
Engine Driver	11537.1
REGULATORS	
Fuel	7341.4
RELAYS	
General	16121.0
RESISTORS, VARIABLE	
General	23333.4

PART TYPE	MTBF (hrs)
SENSORS	
Torque	12500.0
Position Autopilot	20000.0
SHOCK ABSORBERS	41096.5
SLIP RING ASSY	4666.7
SOLENOIDS	10000.0
SWITCHES	
General	10137.9
Centrifugal	7440.7
Float Liquid Level Indicator	21499.8
Pressure, General	3008.6
Pressure, Hydraulic	11126.7
Pushbutton	1404494.4
Rotary	46000.3
Sensitive	203334.7
Thermostatic	24222.5
Toggle	53749.0
SYNCHROS & RESOLVERS	
Synchro General	6666.7
Resolver	1736.8
TANKS	
General	20727.1
Compressed Gas	3846.2
Fuel Cell	9189.1
Oil	7171.4
Reservoir Hydraulic	4063.8
THERMOCOUPLES	15875.0
TIMERS, ELECTRO-MECHANICAL	4139.3
TRANSDUCERS	
General	10000.0
Motional	13999.9
Pressure	6467.4
Tach Generator	9606.3
Temperature	6189.2
TRANSMITTERS	
Pressure	13733.2
VALVES	
Generator	10121.0
Check	99502.5
Relief	6744.5
Shut-Off	32833.2
Solenoid	8025.0
VALVE-FUEL	
Fuel Check and Float	25000.0
Fuel Float	25000.0
Fuel Gate	13999.9
Fuel Pressure Regulator	18077.0
VALVE-HYDRAULIC	
Hydraulic Relief	23333.4
Hydraulic Servo	31666.6
Hydraulic Shut-Off	3333.3
VALVE-PNEUMATIC	
Pneumatic Bleed	4700.0
Pneumatic Relief	102406.6

INSPECTION EFFICIENCY (Table 3-4)

The following boundary diagram provides estimates of efficiency ranges for a variety of inspection methods. The ranges defined by the diagrams were deduced from conversations and interviews with production engineers experienced in the helicopter fabrication process. Estimates of efficiency are based on application of the data collected to the efficiency model alluded to in Section 3.1.4 where detection of a quality defect was defined as a function of AQL, inspection tools, procedures, inspector experience and time for inspection. The ranges for many of the inspection processes identified are quite broad due to the variety of variables which determine inspection efficiency. If on line data collection is achievable, efficiency factors should be calculated and used in place of estimates based on the diagram. If current or historical data on similar inspection procedures is not available, finer estimates should be based on more thorough analysis of the particular inspection technique as discussed in Section 3.2.

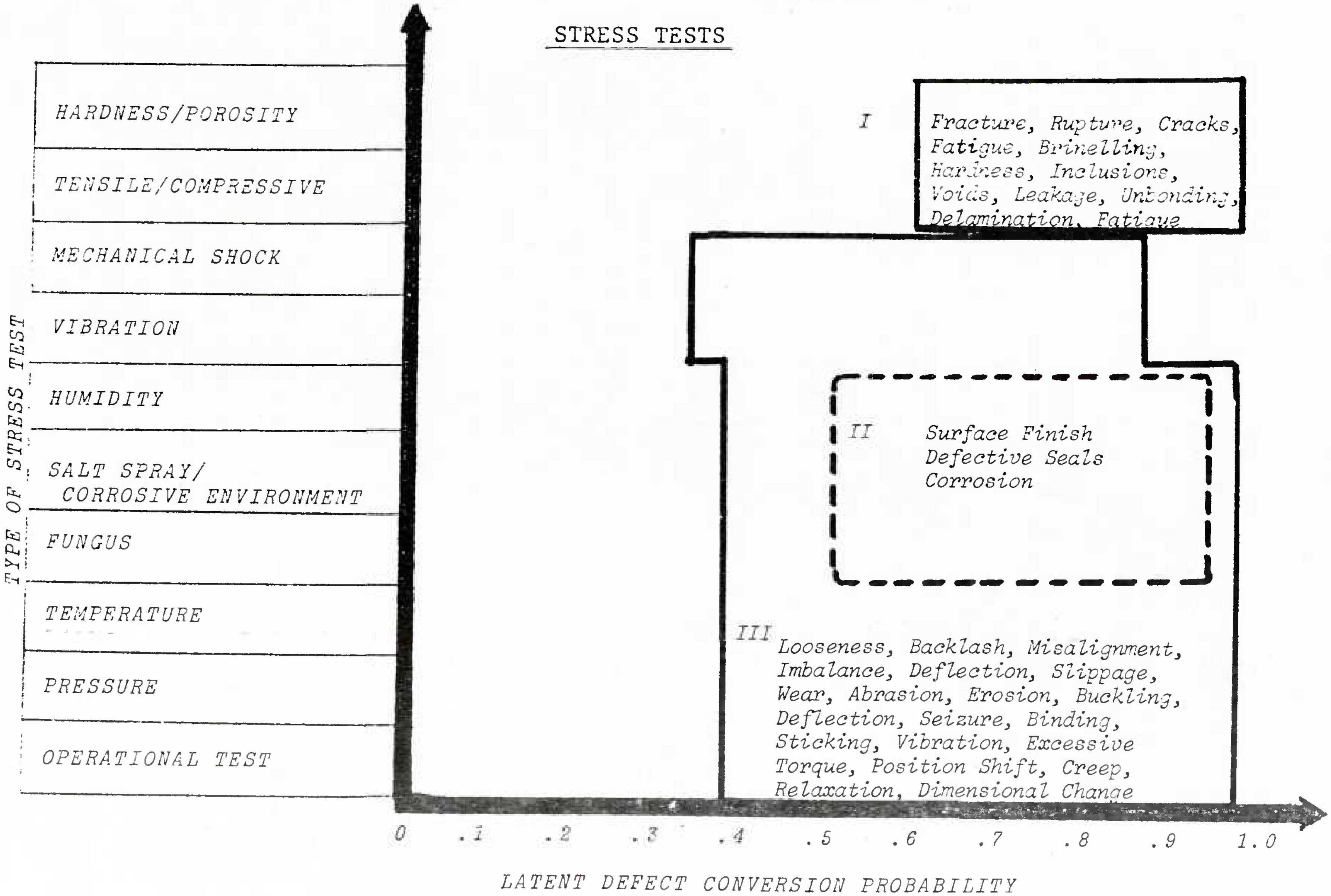
Table 3-4 INSPECTION EFFICIENCY



LOAD TEST CONVERSION EFFICIENCY (Table 3-5)

The following boundary diagram provides estimates of efficiency ranges for a variety of load tests. The ranges defined by the diagrams were deduced from conversations and interviews with production engineers experienced in the helicopter fabrication process. Estimates of efficiency are based on application of the data collected to the model alluded to in Section 3.1.5 where conversion of a latent defect to an observable defect was defined as a function of probability of the defect, the loading device, the load level and operator experience. The ranges for many of the tests identified are quite broad due to test equipment variety. If on line data collection is achievable, efficiency factors should be calculated and used in place of estimates based on the diagram. If current or historical data on similar test procedures is not available, finer estimates should be based on analysis of the test equipment and human factors involved in the defect detection process.

Table 3-5 LOAD TEST CONVERSION EFFICIENCY



DEFECT RATES FOR PRIMARY PROCESSES (Table 3-6)

Primary processes may be defined as those processes which form raw materials into general contours and shapes. Examples of primary processes are part formation by casting, forging or extrusion. Depending on the specific process, varying numbers of defects are introduced in the fabrication operation. Quality defects may manifest themselves as out of tolerance dimensions, flaws in the surface finish or degraded metallurgical quality. Latent defects are introduced through inclusion or residual stresses and voids.

A quantitative estimate of defects introduced in a primary process may be based on the repeatability of the process output with respect to some measurable criteria. It is desirable that this criteria require an assessment of the combined quality and latent defect concentration.

The repeatability numerics compiled in the following tables are derived from tabulations in the AMC Engineering Design Handbook.[7] It has been assumed that nonrepeatability is caused only by quality or latent defects introduced in the production process. Then, a process that is repeatable 90% of the time has a defect rate of 10% (100%-90%). This is interpreted as inducing 10 defects per each 100 process operations. The apportionment of defects into quality and latent categories, depends on the specific process and is best assessed by engineering personnel familiar with the intimate details of the process. The format of the data forms presents general process categories on the left and subcategories of the general process further toward the right. For example, a static coating is a subdivision of the casting process and static casting may be subdivided into die, cast bonding, permanent mold, etc. Finally permanent molds may be divided into slush and mold.

Table 3-6 DEFECT RATES FOR PRIMARY FABRICATION PROCESSES

- PRIMARY FABRICATION
  - CASTING
    - Centrifugal
      - Centrifuge (.1)
      - Semi (.1)
      - True (.1)
    - Semicontinuous (.1)
    - Continuous
      - Dip-Forming (.1)
        - Die
          - Harrison Process (.07)
        - Cast Bonding (.1)
        - Permanent Mold
          - Slush (.1)
          - Mold (.1)
        - Vacuum Casting (.1)
        - Investment (.1)
        - Pressure (.1)
        - Sand
          - Green Sand (.1)
          - Shell-Mold (.1)
          - CO_2-Mold (.1)
          - Core-Mold
            - Baked (.1)
            - Cold-Setting (.1)
    - Static
  - FORGING
    - Die
      - Powder (.05)
      - Harrison Process (.05)
      - Press
        - Cored (.05)
      - Hammer (.05)
    - Upset
      - Press (.05)
      - Hammer (.05)
    - High-Energy Rate (.05)
  - EXTRUSION
    - Hydrostatic (.01)
    - Hot (.01)
    - Cold (.01)
    - Powder
      - Hot (.01)
      - Cold (.01)
    - Impact Extrusion (.01)
  - DRAWING
    - Sheet
      - Plug (.01)
    - Tube (.01)
    - Wire & Rod (.01)
  - ROLLING
    - Hot (.01)
    - Cold
      - Powder (.01)
  - CLADDING
    - Electrocladding (.01)
  - ELECTROFORMING
    - Electrotyping (.01)
  - PIERCING (.05)
  - SWAGING (.05)
  - TUBE REDUCING (.05)
  - POWDER METALLURGY
    - Hot Pressing
      - Isostatic (.05)
      - Reactive (.05)
      - Forging (.05)
      - Extrusion (.05)
      - Solid Die (.05)
    - Powder Sintering
      - Precompacted (.05)
      - Loose (.05)
    - Compaction
      - Pressureless
        - Infiltration (.05)
        - Vibratory (.05)
        - Slip Casting (.05)
      - Pressure
        - Cold Extrusion (.05)
        - Isostatic (.05)
        - Forging (.05)
        - Powder Rolling (.05)
        - Solid Die (.05)
    - Blending (.05)

Number in parenthesis indicates the defect probability.

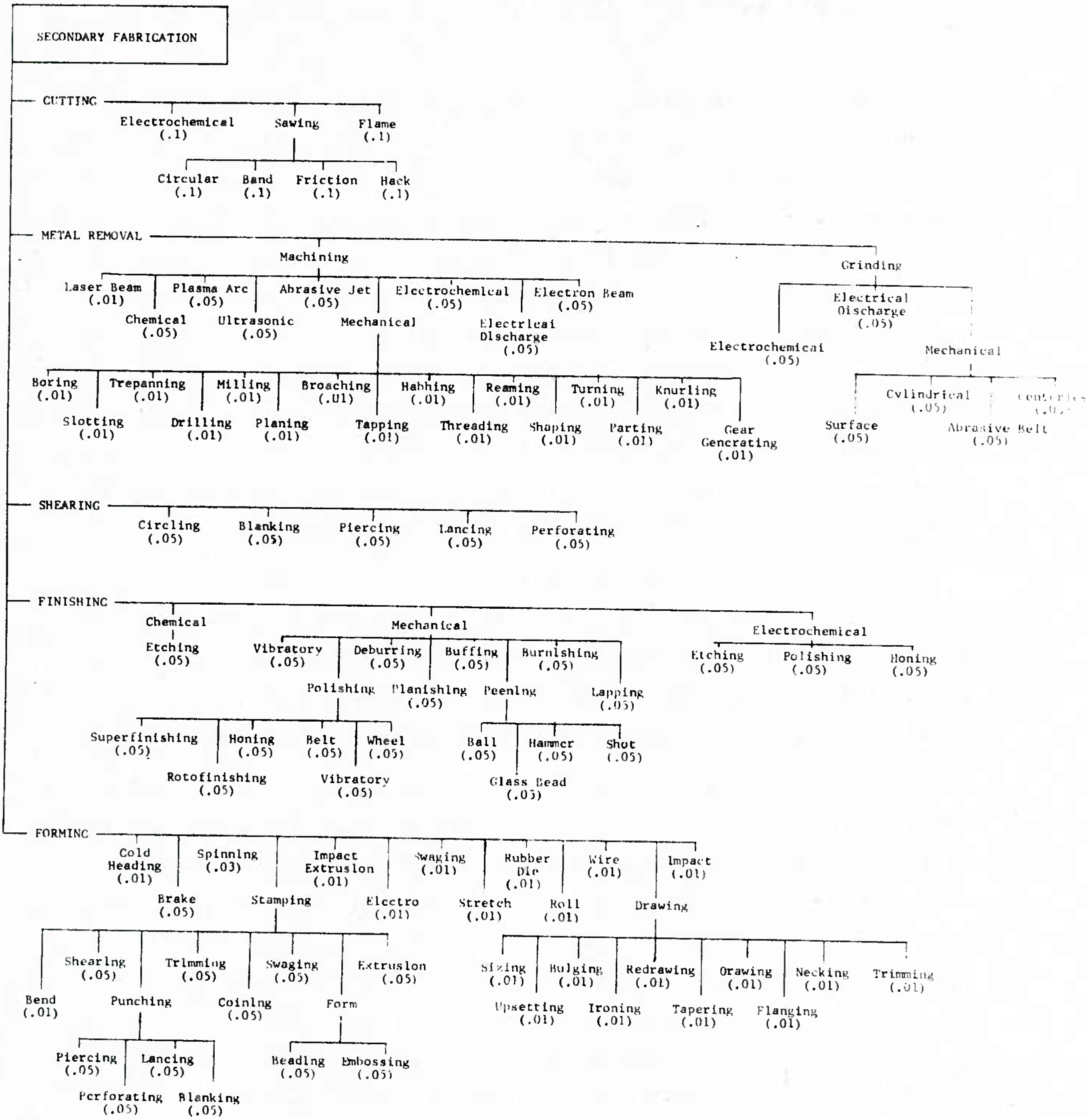
DEFECT RATES FOR SECONDARY PROCESSES (Table 3-7)

Secondary processes may be defined as those processes that involve material removal, cutting and forming operations performed on material to bring it to the dimensions of the finished part. Examples of secondary processes are boring, broaching, drilling, reaming, grinding, cutting, etc. Since secondary processes generally involve machining operations, the rate of defect introduction depends strongly on machinability of the material involved. Depending on the material and particular process, quality defects can be introduced which manifest themselves as out of tolerance, poor surface finish, out of roundness and insufficient flatness or parallelism. Latent defects may take such forms as internal stresses or hidden cracks.

A quantitative estimate of defects introduced in a secondary process may be based on the repeatability of the process output with respect to some measurable criteria. It is desirable that this criteria require an assessment of the combined quality and latent defect concentration.

The repeatability numerics compiled in the following tables are derived from tabulations in the AMC Engineering Design Handbook.[7] It has been assumed that repeatability is caused only by quality or latent defects introduced in the production process. Then, a process that is repeatable 90% of the time has a defect rate of 10% (100%-90%). This is interpreted as inducing 10 defects per each 100 operations. The apportionment of defects into quality and latent categories depends on the specific process and is best assessed by engineering personnel familiar with the intimate details of the process. The format of the data forms presents general categories of processes on the left and subcategories of the general process further toward the right. For example, sawing is a subcategory of cutting and may be achieved by one of four methods - circular, bond, friction or hack.

Table 3-7 DEFECT RATES FOR SECONDARY FABRICATION PROCESSES



Numbers in parenthesis indicate the Defect Probability.

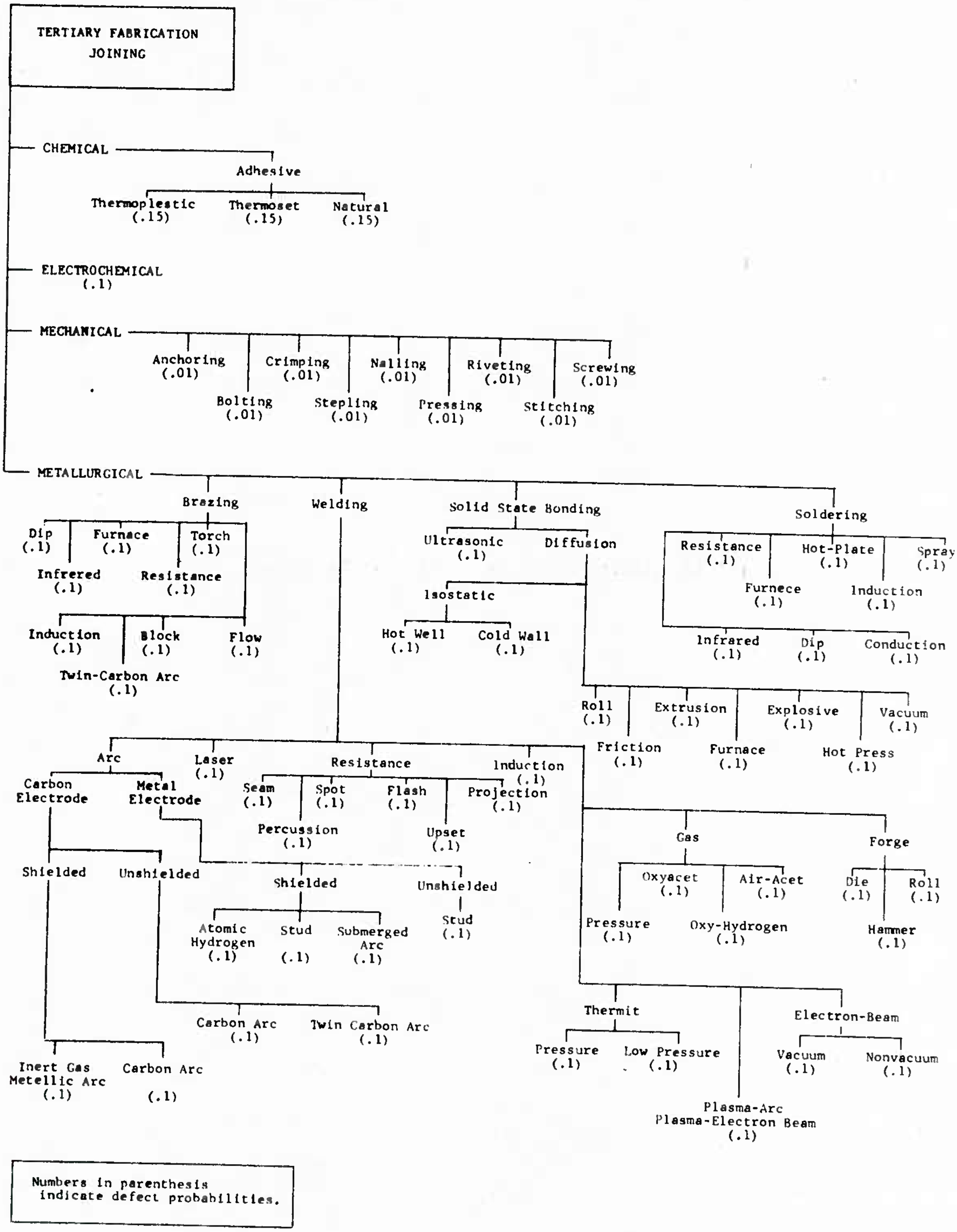
DEFECT RATES FOR TERTIARY PROCESSES (Table 3-8)

Tertiary processes may be defined as those processes which combine subassemblies into the completed assembly. Tertiary process predomenantly involve joining methods. Examples of such processes are welding, soldering and chemical joining. The rate of defect introduction depends on the particular joining process involved. Depending on physical properties of the materials joined and the particular joining process, quality defects can be introduced which manifest themselves as stress cracking, distortions and insufficient clearances. Latent defects may take such forms as embrittlement or changes in mechanical properties due to alteration of the material microstructure.

A quantitative estimate of defects introduced in a tertiary process may be based on the repeatability of the process output with respect to some measureable criteria. It is desireable that this criteria require an assessment of the combined quality and latent defect concentration.

The repeatability of numerics compiled in the following tables are derived from tabulations in the AMC Engineering Design Handbook.[7] It has been assumed that nonrepeatability is caused only by quality or latent defects introduced in the production process. Then a process that is repeatable 90% of the time has a defect rate of 10% (100%-90%). This is interpreted as inducing 10 defects per each 100 process operations. The apportionment of defects into quality and latent categories, depends on the specific process and is best assessed by engineering personnel familiar with the intimate details of the process. The format of the data form presents general categories of processes on the left and subcategories of the general process further to the right.

Table 3-8 DEFECT RATES FOR TERTIARY FABRICATION PROCESSES



4.0 SAMPLE APPLICATIONS

To show how the production reliability model can be applied to the manufacturing of helicopter components, the following examples are presented.

Example 1 evaluates the degradation incurred in the production of a relatively simple part, the bell crank.

Example 2 considers a more complex part consisting of several pieces which are assembled to form a roller bearing.

Example 3 examines the degradation incurred in the assembly of a relatively complex subsystem, the main transmission.

Example 4 considers an intricate assembly operation, fabrication of a main rotor blade.

The following examples are not meant to identify processes incorporated in a specific manufacturer's production facility or to be related to the fabrication of parts or subassemblies of a particular helicopter. The examples are presented here only to illustrate the applications of the procedure discussed in Section 3.2 and demonstrate the use of data tabulations presented in Section 3.3. The analysis of a production process should utilize the entire data field available and apply the examples as guidelines for formulating the production flow and exercising the mathematical methodology.

4.1 EXAMPLE 1: BELL CRANK

The production degradation experienced in the manufacture of a bell crank is discussed in this example. The procedure outlined in Section 3.2 will be followed.

Step 1. Determine Inherent MTBF

For this calculation, it will be assumed that the inherent MTBF is as stated in Table 3-3 (34600 hrs.).

Step 2. Draw Process Diagram

The process diagram is shown in Figure 4-1. The manufacturing process depicted indicates that the bell crank is a relatively simple part to manufacture. The final configuration of the bell crank is shown in Figure 4-2. The part is cast, then inspected, shaped with a mill, drilled and again inspected.

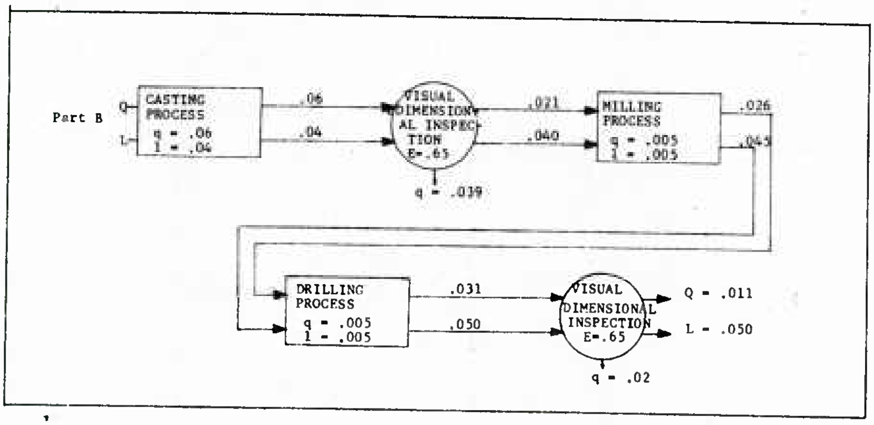


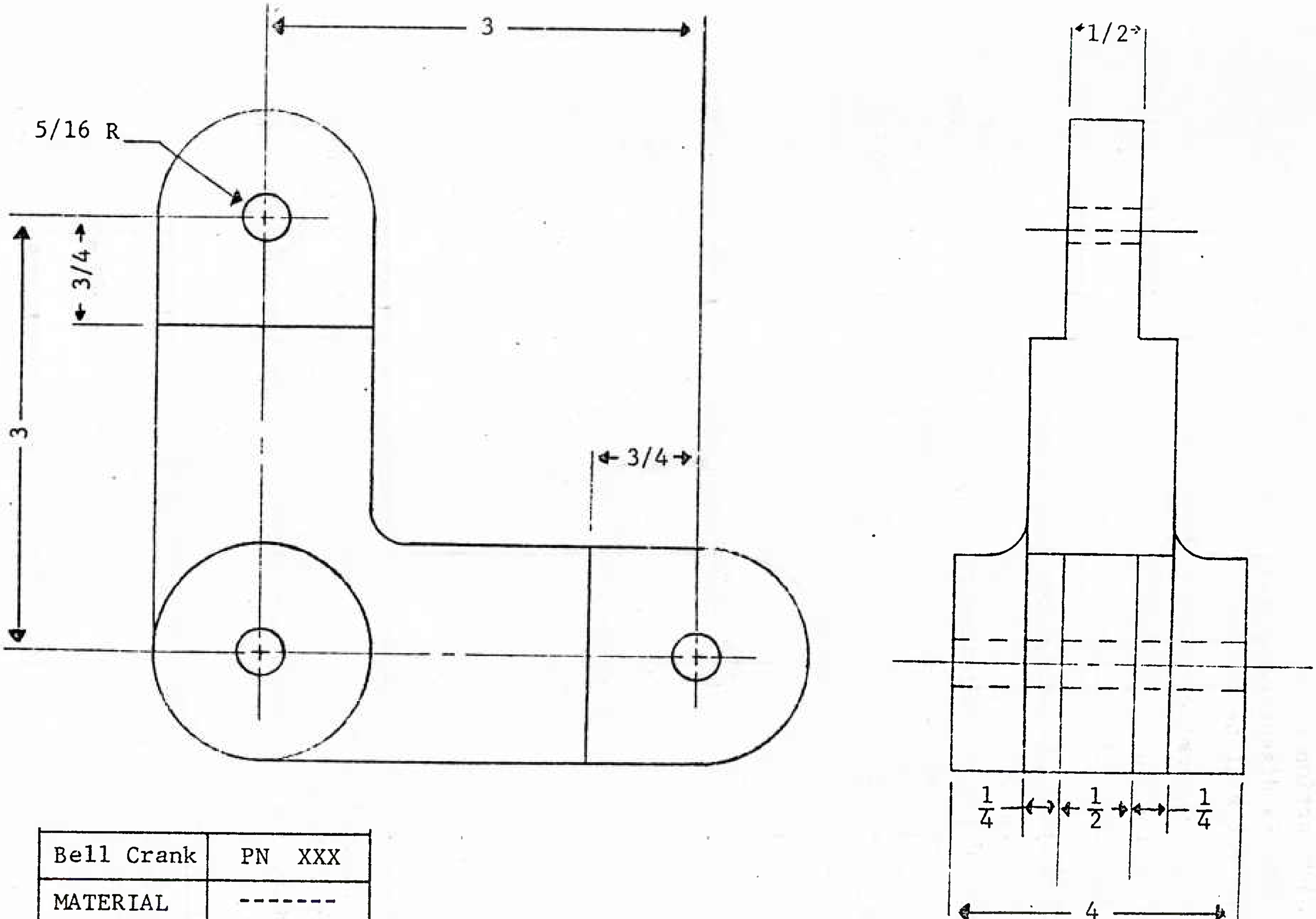
Figure 4-1 PROCESS FLOW DIAGRAM FOR BELL CRANK PRODUCTION

Step 3. Determine Efficiency Factors

All inspections are visual dimensional. From Table 3-4, the efficiency range for this inspection method is E = 0.4 to 0.9. In this example, a value in the middle of that range will be selected. (E = 0.65).

Step 4. Determine Induced Defect Rates

The data in Table 3-6, 3-7 and 3-8 will be used to estimate process induced defect rates. The rate associated with casting



Bell Crank	PN XXX
MATERIAL	--------
TOLERANCES	-------

Figure 4-2 BELL CRANK

is 0.10 (10 defects introduced per 100 castings) as selected from Table 3-6. It is expected that quality defects will be predominant. An allocation of 60% quality and a 40% latent will be arbitrarily choosen. The quality defect rate (.060) and the latent defect rate (.040) are entered into row 1 of Table 4-1. Defects removed by the inspection are calculated using the efficiency factor selected in Step 3. The numeric is entered in row 2. These defects are subtracted and the remaining defects carried forward to row 3 as defects entering the milling process. Milling is a secondary process having a defect rate of .01 as selected from Table 3-7. An equal number of latent and quality defects will be assumed. (5 quality and 5 latent defects per 1000 operations). These defects are added and entered in the fourth row of Table 4-1, as defects present at the start of the drilling process. The defects induced by the drilling process are selected from Table 3-7 assuming an equal apportionment between latent and quality. (5 quality and 5 latent defects per 1000 operations). Drilling process defects are entered into row 4. The induced defects are added to the present defects and entered in row 5 of Table 4-1, as defect rates entering the final inspection. Removed defects are calculated, using the efficiency factor selected in Step 3, and entered in row 5. They are then subtracted, leaving total defects at the end of production. Total defects induced by fabrication and defects removed by inspection and test are also tabulated. The difference between these numerics provides a check on the end of production defect rate.

Step 5. Determine Outgoing Defect Rates

Based on the above steps and the mathematical procedure developed in Section 3.1, the outgoing defect rate is .061.

Step 6. Determine MTBF Degradation

The technique developed in Section 3.1.6 is applied to the evaluation of post production MTBF. An inherent defect rate is determined from Eq. (3-84) using the inherent MTBF from Step 1 to determine operational failure rate ($\lambda_{op} = 1/MTBF_{in}$). The inherent

Table 4-1 CALCULATION OF TOTAL DEFECT RATE

PROCESS DESCRIPTION	DEFECTS PRESENT IN ITEMS		DEFECTS INDUCED BY FABRICATION		DEFECTS REMOVED BY INSPECTION	DEFECTS REMOVED BY SCREEN TEST
	Quality Q	Latent L	Quality q	Latent l	Quality q	Latent l
Casting Process	0	0	.060	.040	—	—
Visual/Dim Inspection	.060	.040	—	—	.039	—
Milling Process	.021	.040	.005	.005	—	—
Drilling Process	.026	.045	.005	.005	—	—
Visual/Dim Inspection	.031	.050	—	—	.020	—
TOTAL	.011	.050	.070	.050	.059	—

Total Defects Present At End of Production = .011 + .050 =	.081
Sum of Entering Defects And Induced Defects	.120
Defects Removed Through Inspection And Tests	.059

defect rate is divided by the post production defect rate to determine the degradation factor. The inherent defect rate (approx. 7 defects per 1000 items) is then multiplied by the degradation factor to determine output MTBF.

$$D_{in} = 1 - e^{-(254)(.000029)}$$

$$D_{in} = 1 - e^{-.00737} = .00734$$

$$MTBF_{out} = MTBF_{in} \frac{D_{in}}{D_{out}}$$

$$MTBF_{out} = (34600)(\frac{.00734}{.061})$$

$$MTBF_{out} = (34600)(.120) = 4160 \text{ hours.}$$

4.2 EXAMPLE 2: ROLLER BEARING

In this example, the model is applied to the analysis of the production degradation experienced in the manufacture of a bearing, a high volume item in the assembly of helicopter subsystems. There are many fundamental types of bearings, such as ball, roller, and sleeve used in the engine, gear box and control mechanisms. The particular bearing selected for an application depends on tradeoffs between standardization, cost, noise, shock resistance, vibration resistance, ease of replacement, complexity and contamination resistance, all of which impact product processes.

The following example discusses the production processes involved in the manufacture of a roller bearing as may be used to support straight spur gears in a transmission. As illustrated below in Figure 4-3, a roller bearing is composed of four basic parts, the inner race, a spacer ring, rollers and an outer ring.

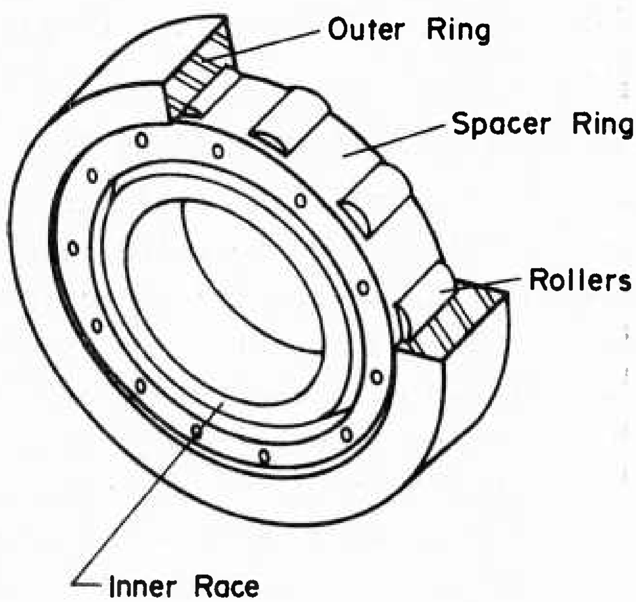


Figure 4-3 CUTAWAY OF CYLINDRICAL ROLLER BEARING

Important quality control considerations in the manufacture of this bearing are inside and outside dimensions, clearance between the inner and outer ring and the rollers, surface finish, surface hardness and uniformity of roller size. Manufacturing processes which influence the attainment of quality requirements for the above considerations are casting, cutting, grinding, deburring, heat treating, cleaning, assembling and inspecting.

The procedure outlined in Section 3.2 is used below:

Step 1. Determine Inherent MTBF

For this calculation it will be assumed that the inherent MTBF is as stated in Table 3-3. (41667 hrs.)

Step 2. Draw Process Diagram

The production flow depicting the sequence of process activities and the related defects introduced and removed by each process is presented in Figure 4-4. Shown are four parallel flows (one for each basic part identified in Figure 4-3) input to an assembly process in which the parts are brought together to complete fabrication. Finally, the completed bearing is inspected and tested.

Step 3. Determine Efficiency Factors

Numerical values quantifying inspection efficiencies are most effectively obtained from relating reject rates to non-detected quality defects outgoing from an inspection station. In the absence of such historical data, ranges of inspection efficiencies may be approximated from models established through examination of a variety of helicopter production lines. During this study ranges corresponding to a number of commonly used inspection methods were derived and are illustrated in Table 3-4 These ranges will be used to estimate efficiencies in this example. Ultrasonic inspection technique efficiencies range from 0.38 to 0.9 (E = 0.8 will be assumed). Dimension inspection efficiency ranges from 0.38 to 0.9 (E = 0.7 will be assumed).

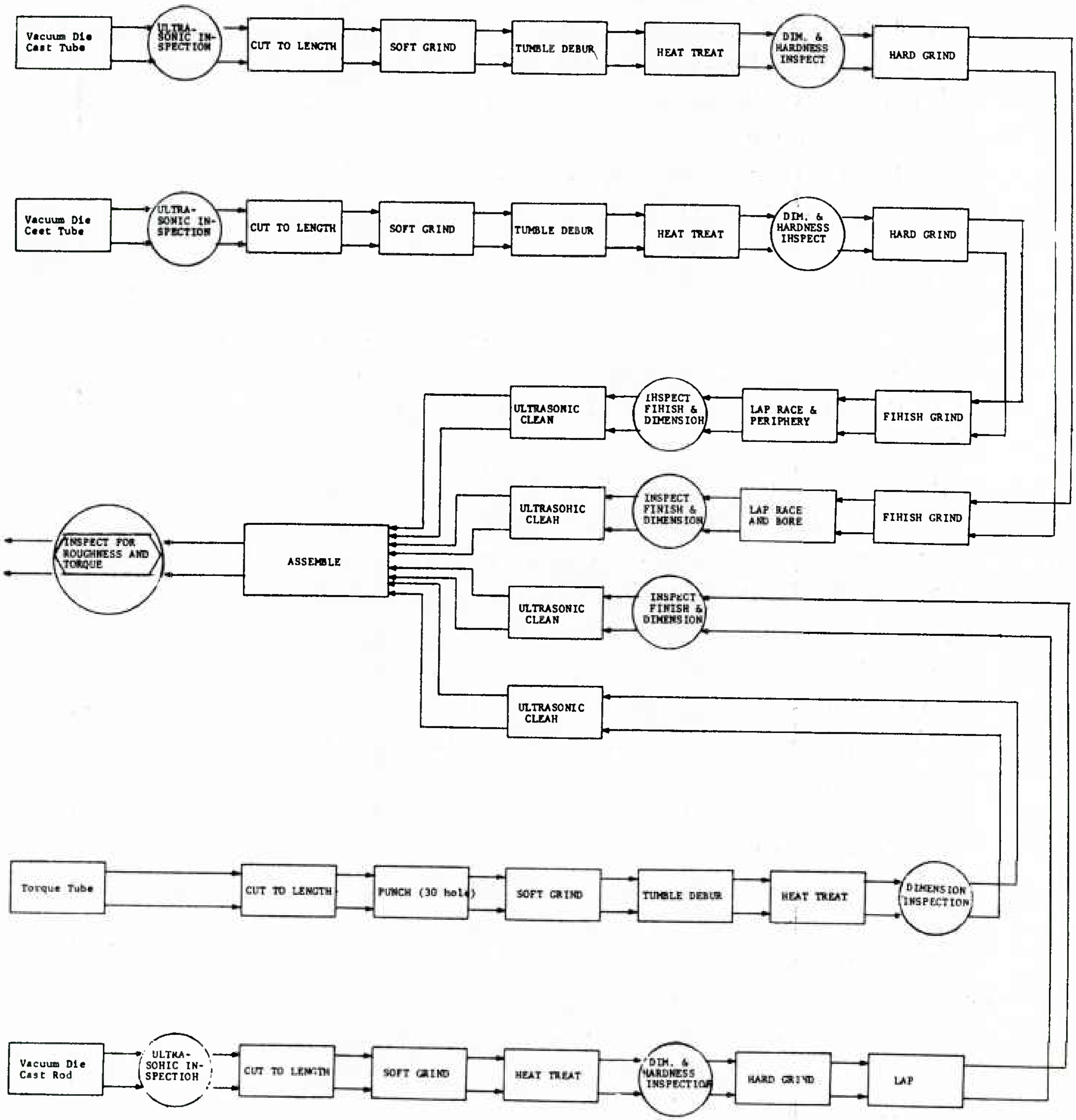


Figure 4-4 MANUFACTURING FLOW CHART FOR ROLLER BEARING

Hardness inspection efficiency ranges from 0.22 to 0.48 (E = 0.35 will be assumed). The combined efficiency for the dimensional and hardness inspection will be assumed to be the product of the individual assumed efficiencies (E = 0.25). Inspection of the finish and dimensions will be assumed to require two independent operations. Associating an efficiency of 0.8 with each, the combined efficiency for both operations will be assumed to be 0.64. A final inspection for roughness is made following assembly. Its efficiency will be assumed to be 0.8.

A final screen test after assembly is made to measure roughness and torque. This is an operational type of stress test and requires a measure of latent defect conversion probability as well as a measure of efficiency to associate numerical values with it. Table 3-5 (Load Test Efficiencies) will be used to approximate latent defect conversion probability. The range for operational stress tests is found to be 0.38 to 0.98 and for this example, a value of 0.65 will be assumed (S = 0.65). The corresponding inspection efficiency will be assumed to be 0.9 (I = 0.9). The roughness inspection is conducted simultaneously with this test to reduce quality defects. An 80% efficiency is assumed (E = 0.80) as stated above.

Step 4. Determine Induced Defect Rates

The association of numerical values to each process may be achieved most reliably through review of manufacturer's historical data derived from the same or similar processes. In the absence of such data, handbook estimates derived from general process repeatability tests may be alluded to. This example will rely totally on such data to demonstrate use of Tables 3-6, 3-7 and 3-8.

The allocation of quality and latent defects is an engineering judgment based on process repeatability and past experience of the interaction of the particular process on the particular material.

In Table 3-6, (Primary Fabrication Processes) an entry is found for vacuum casting. The associated defect probability for this process if P = 0.1 (assume q = 0.08; l = 0.02). In Table 3-7 (Secondary Fabrication Processes) entries are found for cutting (P = 0.1; assume q = 0.1; l = 0), grinding (P = 0.05; assume q = 0.04; l = 0.01), deburring (P = 0.05; assume q = 0.05; l = 0), and heat treatment (P = 0.01; assume q = 0.005; l = 0.005), mechanical lapping (P = 0.05; assume q = 0.05; l = 0), punching (P = 0.05; assume q = 0.03; l = 0.02) and ultrasonic cleaning (P = 0.01; assume q = 0.01; l = 0).

It remains to establish a numerical value for assembly. Assembly involves a sequence of several tertiary processes. Table 3-8 may be used to approximate numerics for the assembly process. The entire assembly process involves several mechanical pressing operations. For simplicity, this example will assume that the combined defect rate for all operations involved in the assembly is P = 0.16 (assume q = 0.06; l = 0.10).

Numerics associated with fabrication processes involving rollers will for this example be assumed to account for the total number of rollers in the bearing.

Step 5. Determine Outgoing Defect Rate

The numerics collected from Steps 3 and 4 are associated with the processes depicted in the flow diagram shown in Figure 4-4. Defect rates introduced by each process and removed by inspection and screen tests are tabulated in Table 4-2 in a step by step manner as the analysis progresses from one process to the next until the assembly operation is reached. Subtotals of induced, removed and remaining defect rates are tabulated for each of the parallel flows at this point. Using the theory developed in Section 3.1 for an assembly process, the subtotals are appropriately combined with defects induced

Table 4-2 CALCULATION OF TOTAL DEFECT RATE

PROCESS DESCRIPTION	DEFECTS PRESENT IN ITEM		DEFECTS INDUCED BY FABRICATION		DEFECTS REMOVED BY INSPECTION	DEFECTS REMOVED BY SCREEN TEST
	Quality Q	Latent L	Quality q	Latent l	Quality q	Latent l
Vacuum Die Cast Tube	0	0	.080	.020	—	—
Ultrsonic Inspection	.080	.020	—	—	.064	—
Cut to Length	.016	.020	.100	0	—	—
Soft Grind	.116	.020	.040	.010	—	—
Tumble Debur	.156	.030	.050	0	—	—
Heat Treat	.206	.030	.005	.005	—	—
Dimension & Hardness Inspection	.211	.035	—	—	.053	—
Hard Grind	.158	.035	.020	.030	—	—
Finish Grind	.178	.065	.030	.020	—	—
Lap Race & Bore	.208	.085	.050	0	—	—
Inspect Finish & Dimension	.258	.085	—	—	.165	—
Ultrasonic Clean	.093	.085	.010	0	—	—
Subtotal	.103	.085	.385	.085	.282	—
Vacuum Die Cast Tube	0	0	.080	.020	—	—
Ultrasonic Inspection	.080	.020	—	—	.064	—
Cut to Length	.016	.020	.100	0	—	—
Soft Grind	.116	.020	.040	.010	—	—
Tumble Debur	.156	.030	.050	0	—	—
Heat Treat	.206	.030	.005	.005	—	—
Dim & Hardness Inspection	.211	.035	—	—	.053	—
Hard Grind	.158	.035	.020	.030	—	—
Finish Grind	.178	.065	.030	.020	—	—
Lop Roll & Periphery	.208	.085	.050	0	—	—
Inspect Finish & Dimension	.258	.085	—	—	.165	—
Ultrasonic Clean	.093	.085	.010	0	—	—
Subtotal	.103	.085	.385	.085	.282	—
Torque Tube	0	0	.050	.050	—	—
Cut to Length	.050	.050	.100	0	—	—
Punch (30 Hole)	.150	.050	.030	.020	—	—
Soft Grind	.180	.070	.040	.010	—	—
Tumble Debur	.220	.080	.050	0	—	—
Heat Treat	.270	.080	.005	.005	—	—
Dim Inspection	.275	.085	—	—	.193	—
Ultrasonic Clean	.082	.085	.010	0	—	—
Subtotal	.092	.085	.285	.085	.193	—
Vacuum Die Cast Rod	0	0	.080	.020	—	—
Ultrasonic Inspection	.080	.020	—	—	.064	—
Cut to Length	.016	.020	.100	0	—	—
Soft Grind	.116	.020	.040	.010	—	—
Heat Treat	.156	.030	.005	.005	—	—
Dim & Hardness Inspection	.161	.035	—	—	.040	—
Hard Grind	.121	.035	.020	.030	—	—
Lap	.141	.065	.050	0	—	—
Inspect Finish & Dimension	.191	.065	—	—	.172	—
Ultrasonic Clean	.069	.065	.010	0	—	—
Subtotal	.079	.065	.305	.065	.226	—
Assemble	.377	.320	.060	.100	—	—
Inspect for Roughness & Torque	.487	.420	—	—	.350	.246
TOTAL	.087	.174	1.470	.420	1.333	.246

Total Defects Present At End of Production = .087 + .174 = .261
Sum of Entering Defects And Induced Defects 1.840
Defects Removed Through Inspections & Tests = 1.333 + .246 = 1.579

by the assembly operation (see Eqs. 3-26 and 3-27). Defects removed by a final inspection and operational test are calculated and recorded in Table 4-2. Finally, Table 4-2 is used to combine all subtotals and obtain total defects introduced in the manufacturing process, total defects removed and defects remaining at the end of production. Note that the approximations, Eqs. (3-26) and (3-27) have been applied to calculate the defect rate leaving the assembly process. Due to relatively large input defect rates, the result may be slightly in error.

Step 6. Determine MTBF Degradation

The technique developed in Section 3.1.6 is applied to the evaluation of post production MTBF. An inherent defect rate is determined from Eq. (3-84) using the inherent MTBF from Step 1 to determine operational failure rate ($\lambda_{op} = 1/MTBF_{in}$). The inherent defect rate (approx. 6 defects per 100 items) is divided by the post production defect rate to determine the degradation factor. The inherent defect rate is then multiplied by the degradation factor to determine output MTBF.

$$D_{in} = 1 - e^{(254)(.000024)}$$

$$D_{in} = 1 - e^{-.00610} = .00608$$

Using Beals modification of eq 3-85

$$MTBF_{out} = 41667 \; \frac{.00608}{.261}$$ = .0962 ← Din

1264

using JJ method!

$$MTBF_{out} = 41667 \; (.0233)$$ MTBF out = 31586.8

$$= 971 \text{ hours}$$

4.3 EXAMPLE 3: MAIN TRANSMISSION

The third example presented here is the main transmission. This unit has been selected because it is a critical item in the performance and survivability of a helicopter and only tertiary fabrication processes are used in its assembly.

The primary function of the main transmission is to transmit the power from the engine(s) to the main rotor. The torque supplied to the rotor results in reaction loads of thrust, moment, and side force in addition to torque that must be reacted by the transmission. The transmission normally transmits all loads via its mounts to the helicopter structure. An alternate solution to supporting the loads imposed by the rotor is to provide a stationary mast or standpipe that carries the rotor support bearings and transmits all loads except torque directly to the helicopter structure. A quill from the transmission supplies torque to drive the tail rotor. Where possible, it is advisable to react all rotor loads to the airframe through a forging that is located so that rotor loads do not pass through any gear support housing. The transmission is a reducing drive to give low speed and high torque to the rotor. Typically, the axis of rotation of the input is horizontal and the output vertical. Secondary outputs for the generator, oil pump, and tail rotor drive are also obtained through gearing in the transmission. These power requirements amount to less than 15% of the maximum power applied to the transmission.

The analysis of the production reliability degradation of a complex subassembly like a transmission is based on knowing defect rates of the parts which make up the transmission, assessing the defect rates induced in the assembly process and establishing the rate at which defects are removed by inspections and tests. The procedure for combining these defect rates to determine degradation was established in Section 3.2 and is applied to the main transmission as presented below.

Step 1. Determine Inherent MTBF

Defect rates of transmission parts may be generally found in historical data tabulations such as the RADC Nonelectric Reliability Notebook.[8]

The actual application of this technique to obtain a realistic prediction of output MTBF requires exercise of detailed modeling techniques to assess inherent reliability or a data base collected from field characteirstics allowing establishment of subassembly inherent values.

Since the objective of this example is not to perform a detailed inherent reliability analysis of complex machinery such as a transmission, but to demonstrate a methodology for predicting degradation of this value by manufacturing processes, the calculation will determine the degradation factor only and the result expressed in terms of the ratio of output MTBF to inherent MTBF.

Step 2. Draw Process Diagrams

The process flow diagram describing the step-by-step transmission assembly is presented in Figure 4-5. As configured, several installations occur in parallel. The components of one assembly require the installation of the quill in the support case and the installation of the two bearings in the main case. In this assembly, case quills are installed prior to an inspection. Following the inspection, manifold and jets are installed and the sump assembly incorporated into the buildup. Parallel to this buildup, three other buildup operations occur.

1. Three bearings and sun gears are installed in a liner and inspected.
2. Jets are installed in the ring gear case.
3. Miscellaneous hydraulic fittings are installed in the top case.

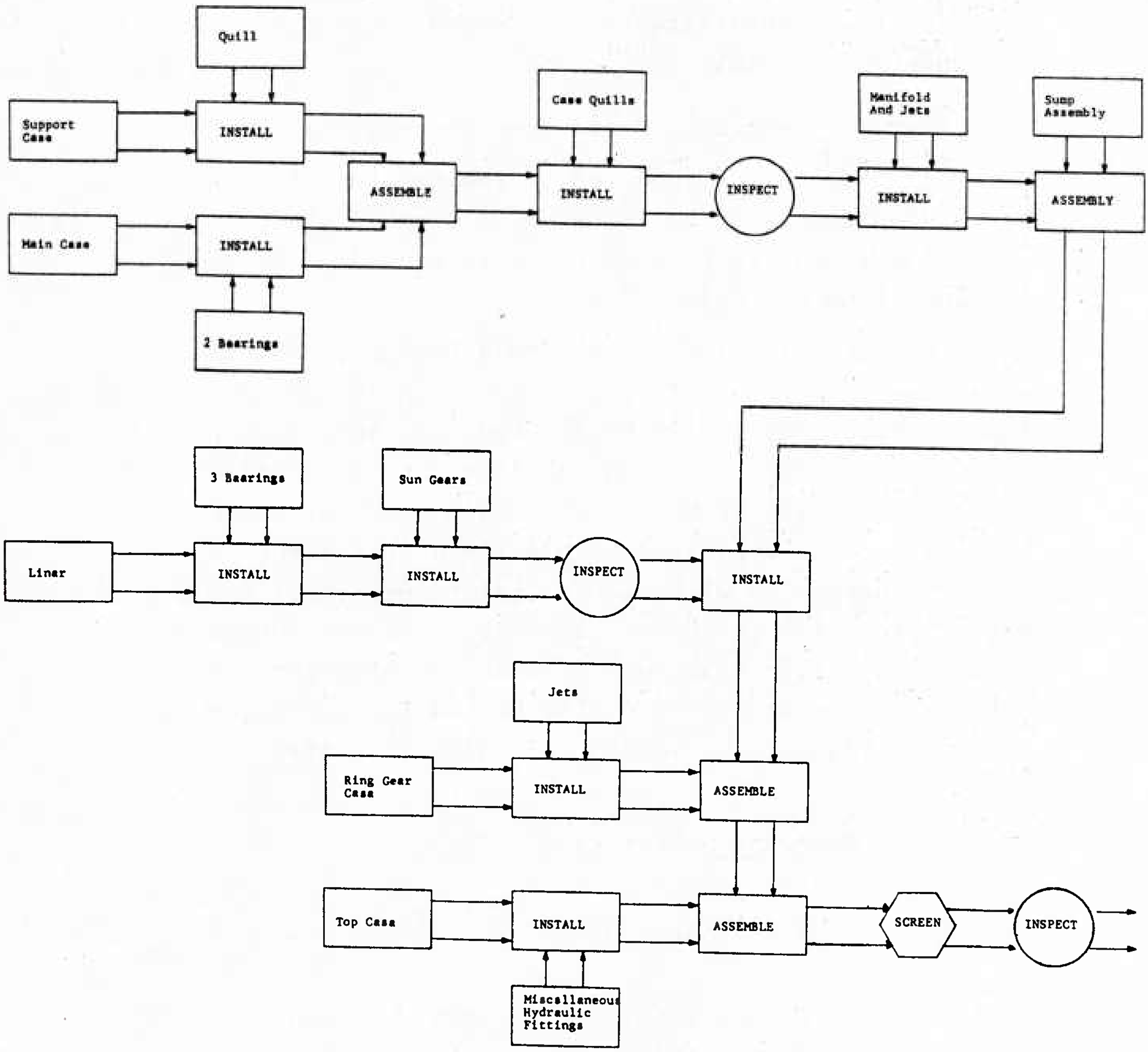


Figure 4-5 MANUFACTURING FLOW CHART FOR MAIN TRANSMISSION
(FOR ASSEMBLY ONLY)

The three subcomponents built up above are then installed into the primary buildup to complete the transmission assembly. Finally, the transmission is subjected to an operational test and undergoes a final inspection.

Step 3. Determine Efficiency Factors

All inspections involved in the transmission assembly will be assumed to be of the visual-dimensional type. The range of efficiencies for such inspections is indicated by Table 3-4 to range from E = 0.4 to 0.9.

This example will illustrate a technique for actually measuring inspection efficiencies for an operating production line. Reject rates will be assumed available from normal production documentation and quality control station outgoing defect rates will be measured. Measurement of outgoing defect rates may be accomplished by placing a very carefully controlled quality inspection with highly trained personnel and sophisticated inspection equipment temporarily at the output of the normal inspection station. Elements passing through the normal inspection station are reinspected for undetected quality defects. The data collected and calculated efficiencies are given below.

Station	Outgoing Defect Rate (Q_{out})	Reject Rate (q_r)	Efficiency $\left(E=\frac{q_r}{Q_{out}+q_r}\right)$
1	88 per 1000	133 per 1000	.6
2	58 per 1000	137 per 1000	.7
3	43 per 1000	388 per 1000	.9

The conversion efficiency of the operational test will be assumed to be S = 0.5 and the detection efficiency is assumed to be I = 0.8 for purpose of this example.

Step 4. Determine Induced Defect Rates

Defect rates used in this example are based on data compilations in Table 3-8 and engineering judgements. Specific defect rates associated with each process and their allocation into latent and quality categories is presented in Table 4-3. In this example it will be assumed that one defect is induced for every 100 parts installed. It will be further assumed that an assembly operation introduces one defect for each 100 components assembled. For simplicity, quality and latent defects will be equally allocated for installation and assembly operations ($q = 0.005$ and $1 = 0.005$).

Step 5. Determine Outgoing Defect Rate

Based on the above steps, all required data inputs have been collected to exercise the mathematical methodologies derived in Section 3.1. The defect rates associated with each component in the assembly and the defect rates introduced by the assembly and installation processes are entered in Table 4-3 in the sequence indicated by the process flow diagram (Figure 4-5). In Table 4-3, parallel strings of processes are subtotaled. For serial combinations, a running account is kept of the defect concentration at any point in the subassembly operation. Subtotals are formed at each assembly or installation process indicating the total defects present at the end of the subassembly or installation, the total defects induced by all processes to that point and the total defects removed by inspections and tests. After the final assembly, the defects removed by a screen test and inspection are entered in Table 4-3. Then the total defects entering and induced by the manufacturing process, the total defects removed by inspection and test, and the defects remaining in the transmission are tabulated.

Table 4-3 CALCULATION OF TOTAL DEFECT RATE

PROCESS DESCRIPTION	DEFECTS PRESENT IN ITEM		DEFECTS INDUCED BY FABRICATION		DEFECTS REMOVED BY INSPECTION	DEFECTS REMOVED BY SCREEN TEST
	Quality Q	Latent L	Quality q	Latent l	Quality q	Latent l
Support Case	.040	.010	—	—	—	—
Quill	.008	.002	—	—	—	—
Installation	.048	.012	.005	.005	—	—
Subtotal	.053	.017	.005	.005	—	—
Main Case	.040	.010	—	—	—	—
2 Bearings	.100	.050	—	—	—	—
Installation	.140	.060	.005	.005	—	—
Subtotal	.145	.065	.005	.005	—	—
Assembly	.198	.082	.010	.010	—	—
Subtotal	.208	.092	.010	.010	—	—
Case Quills	.008	.002	—	—	—	—
Installation	.216	.094	.005	.005	—	—
Subtotal	.221	.099	.005	.005	—	—
Inspection	.221	.099	—	—	.133	—
Subtotal	.088	.099	—	—	.133	—
Manifold & Jets	.080	.020	—	—	—	—
Installation	.168	.119	.005	.005	—	—
Subtotal	.173	.124	.005	.005	—	—
Sump Assembly	.040	.060	—	—	—	—
Assembly	.213	.184	.010	.010	—	—
Liner	.040	.010	—	—	—	—
3 Bearings	.100	.050	—	—	—	—
Installation	.140	.060	.005	.005	—	—
Subtotal	.145	.065	.005	.005	—	—
Sun Gears	.040	.010	—	—	—	—
Installation	.185	.075	.005	.005	—	—
Subtotal	.190	.080	.005	.005	—	—
Inspection	.190	.080	—	—	.133	—
Subtotal	.057	.080	—	—	.133	—
Installation	.280	.274	.005	.005	—	—
Subtotal	.285	.279	.005	.005	—	—
Ring Gear Case	.040	.010	—	—	—	—
Jets	.050	.010	—	—	—	—
Installation	.090	.020	.005	.005	—	—
Subtotal	.095	.025	.005	.005	—	—
Assemble	.380	.304	.010	.010	—	—
Subtotal	.390	.314	.010	.010	—	—
Top Case	.040	.010	—	—	—	—
Misc. Fittings	.050	.100	—	—	—	—
Installation	.090	.110	.005	.005	—	—
Subtotal	.095	.115	.005	.005	—	—
Assembly	.485	.429	.010	.010	—	—
Subtotal	.495	.439	.010	.010	—	—
Screen Test	.495	.439	—	—	—	.180
Inspection	.495	.259	—	—	.455	—
Subtotal	.040	.259	—	—	.455	.180
TOTAL	.040	.259	.085	.085	.746	.180

Total Defects Present At End of Production = .040 + .259 = .299
Sum of Entering And Induced Defects 1.225
Defects Removed Through Screens and Tests = .746 + .180 = .926

Step 6. Determine MTBF Degradation

The technique developed in Section 3.1.6 is applied to the evaluation of post production MTBF. The inherent defect rate is expressed as a function of inherent MTBF ($\lambda_{op} = 1/MTBF_{in}$). The inherent defect rate is divided by the post production defect rate to determine the degradation factor. Since a specific MTBF value was not stated in Step 1, the output MTBF will be expressed as a function of the inherent MTBF value and the induced defect rate (299 defects per 1000 items).

$$D_{in} = 1 - e^{254\lambda_{op}} = 1 - e^{-254/MTBF_{op}}$$

$$MTBF_{out} = \frac{MTBF_{in}(1 - e^{-254/MTBF_{in}})}{.299}$$

4.4 EXAMPLE 4: ROTOR BLADE

The final example to be illustrated here in the fabrication of a rotor blade. The rotor has been selected because it is a critical element in the survivability of the helicopter. It is used only in the helicopter industry and the production process has not matured because of the limited number produced to date. Its value as an example is that it uses fabrication techniques not illustrated previously.

The rotors used in helicopters find almost no counterpart elsewhere and are unique in their operating conditions. The rotor must provide thrust and lift for sea level hovering and an additional margin of thrust for vertical climb and hovering at higher altitudes. In flight the rotor provides the propulsive thrust as well as the lift to sustain the aircraft. The rotor also provides the required helicopter control forces for roll and pitch as well as acceleration fore, aft, laterally, and vertically. As the rotor moves through the air in flight, it experiences changes in airflow that give rise to periodic fluctuations of aerodynamic forces and loads.

A rotor is shown in Figure 4-6 with sectional views of the center section and the rotor to spar union. This rotor blade is an all-metal construction with an aluminum alloy honeycomb core, aluminum skin and nose block. All structural components are joined by metal to metal bonding. The blades are set in hub grips at a preconing angle and secured by a single retaining bolt in each grip. A trim tab is provided on the trailing edge for tracking adjustments.

The production reliability degradation incurred in the manufacture of a rotor blade is assessed in terms of the procedure developed in Section 3.2 and presented as follows.

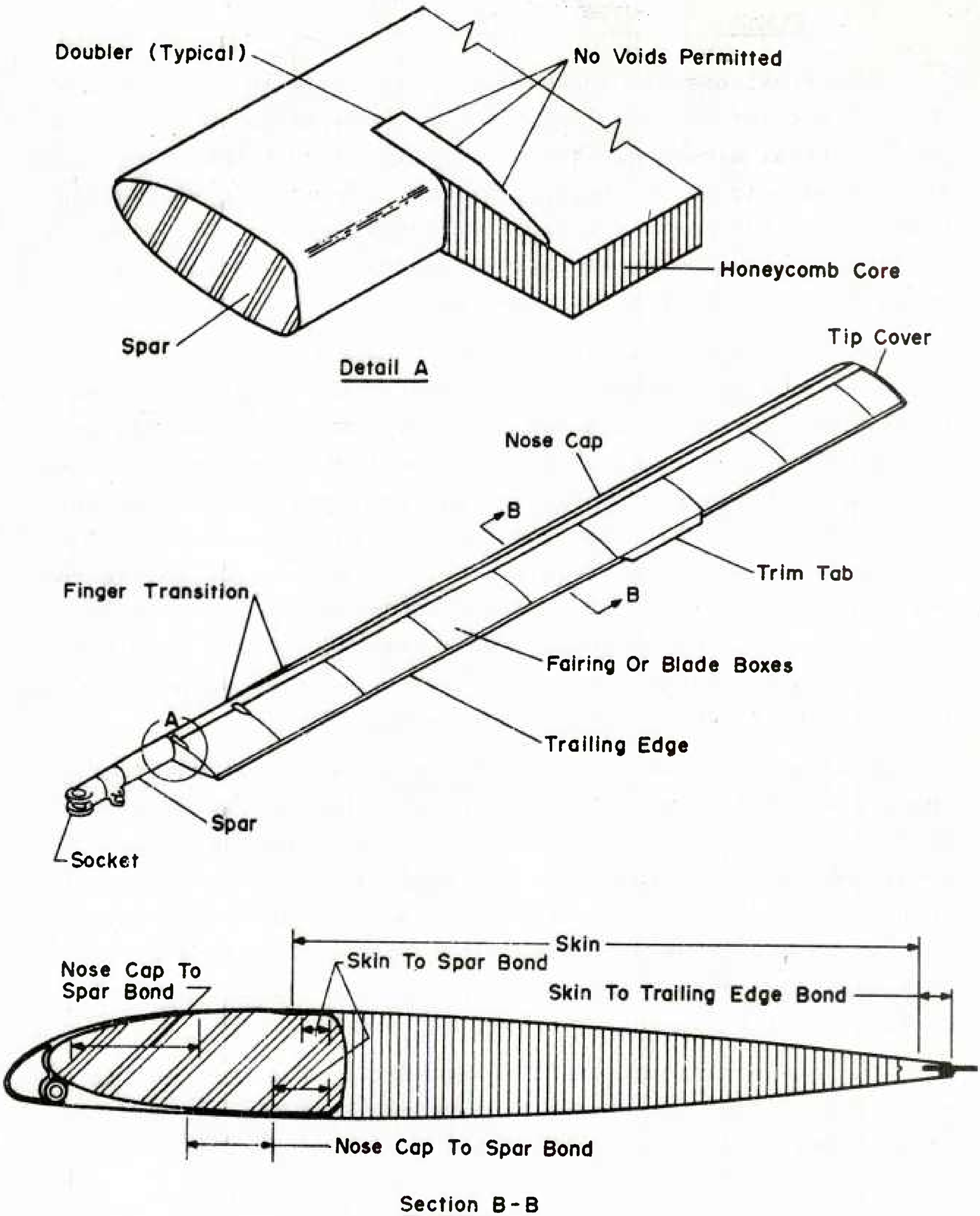


Figure 4-6 ROTARY WING BLADE

Step 1. Determine Inherent MTBF

In this example, it will be assumed that the rotor blade is in the design stage and a firm inherent MTBF has not been established since the design is not yet fixed. The objective is only to calculate the production degradation factor to assess if the design should be altered in a manner to reduce production degradation.

Step 2. Draw Process Diagram

Shown in Figure 4-7 is the manufacturing process flow. Three fabrication processes occur in parallel, each originating with an inspection of raw materials.

1. Spars are machined.

2. Aluminum skin is bonded to doublers and ultrasonically inspected.

3. Honeycomb is cut, shaped and dimensionally inspected.

Subassemblies resulting from the three fabrications are assembled in an operation in which the honeycomb is bonded to the skin spars. The resulting bond is tested. Next, a leading edge is machined and bonded to the blade. The curing cycle is monitored and a pull test is applied. Finally, the tip is assembled to the blade and the entire blade subjected to a final inspection.

Step 3. Determine Efficiency Factors

Due to the criticality of the machine spars in preserving the integrity of the rotor blade, the incoming inspection is certified to assure a high level of inspection efficiency. Based on the certification and the range of efficiencies for inspections given in Table 3-4, a value of $E = 0.9$ will be used. Raw material inspections initiating other fabrication processes are not as critical and corresponding efficiencies will be assumed to be lower $E = 0.8$. The curing cycle is monitored and also certified to assure high efficiency. The value selected is assumed slightly lower than that for a certified raw material inspection since inadequate curing is

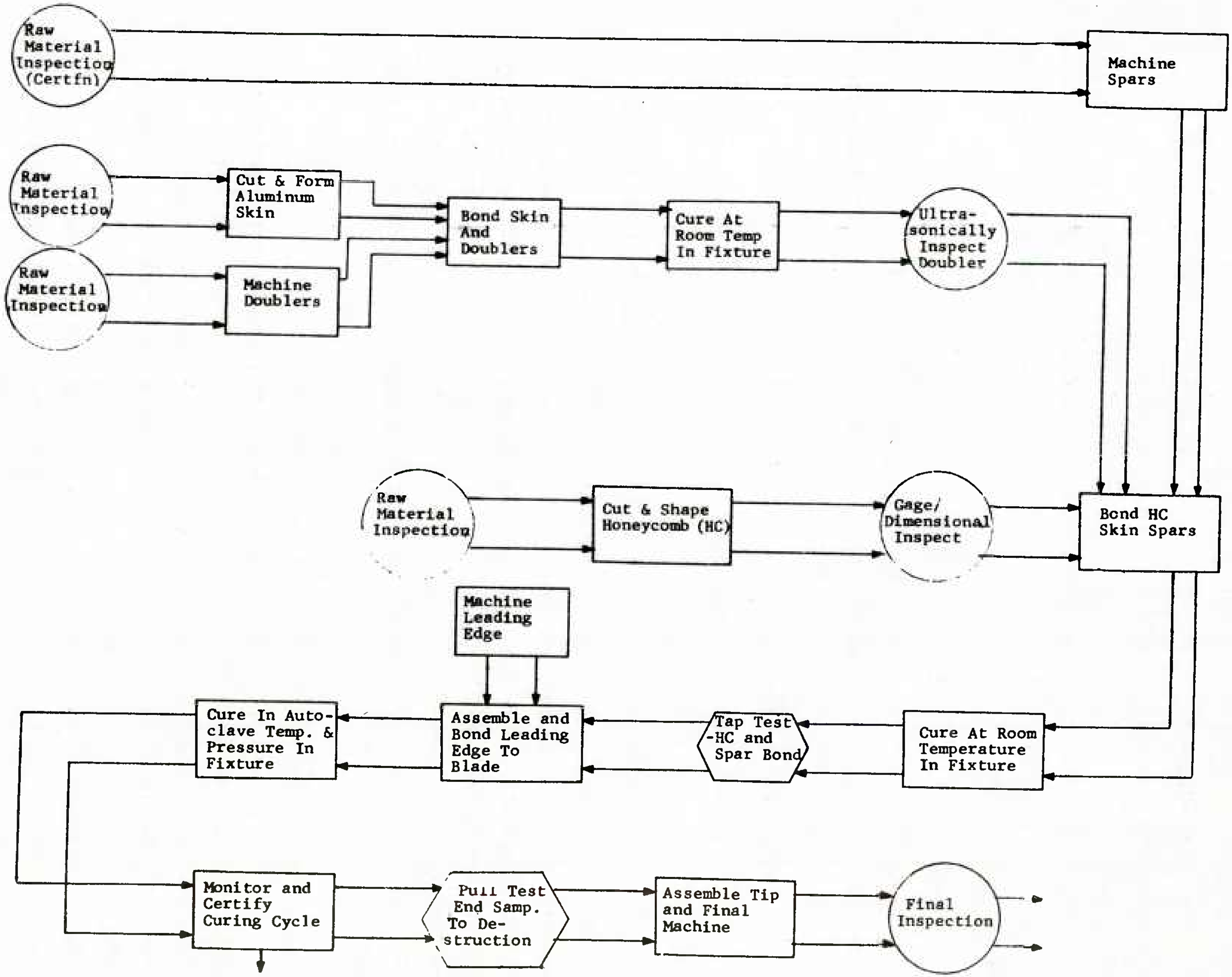


Figure 4-7 MANUFACTURING FLOW CHART FOR ROTOR BLADE

more difficult to detect than raw material quality defects. The efficiency to be used is E = 0.85. The doubler inspection is ultrasonically performed. Its efficiency will be selected as the midpoint of the range shown in Table 3-4. (E = 0.65). The gage dimensional inspection efficiency will be selected as E = 0.7 and the final inspection efficiency as E = 0.6. The relatively low value for the final inspection is based on only external defects being observable.

The pull test conversion efficiency will be assumed to be within the range specified for tensile/compressive tests given in Table 3-4. The associated detection efficiency will be assumed to be I = 0.9.

The tap test will be assumed to be 50 percent efficient (E = 0.5).

Step 4. Determine Induced Defect Rates

Raw material defect rates will be assumed to be .001, twenty percent of the defects being latent and eighty percent being quality. Numerical values for process induced defects will be selected from Tables 3-6, 3-7 and 3-8. Machining operations will be allocated an induced defect rate of .01 and assumed to be made up of half latent and half quality defects. Cutting operations will be allocated an induced defect rate of 0.1 and increased by 20 percent if forming or shaping is included as part of the process. Sixty percent of the defects shall be assumed latent and forty percent quality. Bonding operations will be allocated an induced defect rate of 0.02 and assumed to include the curing operation. The defect makeup shall be assumed eighty percent latent and twenty percent quality. Assembly operations will be allocated an induced defect rate of 0.01 per each component assembled and equally divided among latent and quality defects.

Step 5. Determine Outgoing Defect Rate

Process defect numerics are combined using the mathematical technique developed in Section 3.1 and presented in the sequence of the process flow in Table 4-4. In Table 4-4, parallel strings of processes are subtotaled. For serial combinations, a running account is kept of the defect concentration at any point in the subassembly operation. Subtotals are formed at each assembly or installation process indicating the total defects present at the end of the subassembly or installation, the total defects induced by all processes to that point and the total defects removed by inspections and tests. After the final inspection, Table 4-4 tabulates totals of defects entering and induced in the manufacturing process, defects removed by inspections and tests and defects remaining in the rotor blade.

Step 6. Determine MTBF Degradation

The technique developed in Section 3.1.6 is applied to the evaluation of post production MTBF. The inherent defect rate is expressed as a function of inherent MTBF ($\lambda_{op} = 1/MTBF_{in}$). The inherent defect rate is divided by the post production defect rate to determine the degradation factor. Since a specific MTBF value was not stated in Step 1, the output MTBF will be expressed as a function of the inherent MTBF value and the induced defect rate (0.0447).

$$D_{in} = 1 - e^{254\lambda_{op}} = 1 - e^{-254/MTBF_{op}}$$

$$MTBF_{out} = \frac{MTBF_{in}(1 - e^{-254/MTBF_{in}})}{0.0447}$$

Table 4-4 CALCULATION OF TOTAL DEFECT RATE

PROCESS DESCRIPTION	DEFECTS PRESENT IN ITEMS		DEFECTS INDUCED BY FABRICATION		DEFECTS REMOVED BY INSPECTION	DEFECTS REMOVED BY SCREEN TEST
	Quality Q	Latent L	Quality q	Latent l	Quality q	Latent l
Raw Material Inspection	.0008	.0002	——	——	.0007	——
Machine Spars	.0001	.0002	.005	.005	——	——
Subtotal .0051	.0051	.0052	.005	.005	.0007	——
Raw Material Inspection	.0008	.0002	——	——	.0006	——
Cut & Form Aluminum Skin	.0002	.0002	.072	.048	——	——
Subtotal	.0722	.0482	.072	.048	.0006	——
Raw Material Inspection	.0008	.0002	——	——	.0006	——
Machine D Doublers	.0002	.0002	.005	.005	——	——
Subtotal	.0052	.0052	.005	.005	.0006	——
Bond Skin & Doublers and Cure	.0774	.0534	.004	.016	——	——
Ultrasonic Inspect Doubler	.0814	.0694	——	——	.0529	——
Subtotal	.0285	.0694	.004	.004	.0529	——
Raw Material Inspection	.0008	.0002	——	——	.0006	——
Cut & Shape Honeycomb	.0002	.0002	.072	.048	——	——
Gage/Dimension Inspection	.0722	.0482	——	——	.0505	——
Subtotal	.0217	.0482	.072	.048	.0511	——
Bond HC Skin Spars	.0553	.1228	.004	.016	——	——
Tap Test HC & Spar Bond Inspection	.0593	.1388	——	——	.0297	——
Subtotal	.0296	.1388	.004	.016	.0297	——
Machine Leading Edge	.0050	.0050	——	——	——	——
Assemble & Bond Leading Edge to Blade & Cure	.0346	.1438	.005	.005	——	——
Monitor and Certify Curing Cycle	.0396	.1488	——	——	.0337	——
Pull Test End	.0059	.1488	——	——	——	.1205
Assemble Tip and Final Machine	.0059	.0283	.010	.010	——	——
Final Inspection	.0159	.0383	——	——	.0095	——
TOTAL	.0064	.0383	.177	.153	.1789	.1205

Total Defects Present At End of Production = .0064 + .0383 = .0447
Sum of Entering And Induced Defects .3441
Defects Removed Through Inspection & Tests = .1789 + .1205 = .2994

5.0 RELIABILITY IMPROVEMENT AND GROWTH

This section discusses reliability growth models and describes how the production reliability model can be applied to improve, control and grow reliability. In order to establish an engineering preamble, basic modeling concepts are first discussed (Section 5.1), next reliability growth testing, as it can be applied during product development, is discussed (Section 5.2) and finally, reliability improvement and growth during production (through application of the Reliability Model) is described (Section 5.3).

5.1 Reliability Growth and Modeling Concepts

The development of growth models provides a tool to infer future reliability from present system reliability or estimate the degree of growth required over some time period to achieve a future reliability goal. Reliability growth models can be used for planing and resource allocation in conjunction with growth test activities during development. As such, they serve as estimators of the total test and product improvement time needed to grow to a given reliability value under various levels of corrective action. In this capacity, growth models become valuable management tools providing insight into cost, schedule and test regimen needed to grow reliability to a desired value during development.

A further use of growth models is that of describing the changes in system reliability during a total development and product improvement program. Thus, the actual system reliability growth can be shown in relationship to project growth curves.

In general, the purpose of most reliability growth models includes one or both of the following:

- Inference from the present system reliability;
- Projection on the system reliability at some future development time.

Most of the reliability growth models considered in the literature assume that a mathematical formula (or curve) as a function of time, represents the reliability of the system during the development and product improvement cycle. It is commonly assumed also that these curves are non-decreasing. That is, once the system's reliability has reached a certain level, it will not drop below this level during the remainder of the development program. It is important to note that this is equivalent to assuming that any design or engineering changes made during the development cycle do not decrease the system's reliability.

If, before the development program has begun, the exact shape of the reliability growth curve is known for a certain combination of system design and development effort, then the model is a deterministic one. In this case, the amount of development effort needed to meet the reliability requirement could be determined, and the sufficiency of the design would, also, be known.

In most situations encountered in practice, the exact shape of the reliability growth curve will not be known before the development program begins. The program manager may, however, be willing to assume that the curve belongs to some particular class of parametric reliability growth curves. This is analogous to life testing situations when the experimenter assumes that the life distribution of the items is a member of some parametric class such as the exponential, gamma, or Weibull families. The analysis then reduces to a statistical problem of estimating the unknown parameters from the experimental data. These estimates may be revised as more data are obtained during the progress of the development program. Using these estimates, the program manager can monitor and project the reliability of the system and make necessary decisions accordingly.

Some Bayesian reliability growth models have also appeared in the literature. This approach assumes that the unknown parameters of the growth curve are themselves random variables governed by appropriate prior probability distributions. Generally, the form of the prior probability distributions are assumed to be known, and the unknown parameters of the reliability growth curve may be estimated with the aid of Bayes Theorem.

Other models considered in the literature may be classified as nonparametric. This approach allows for the estimation of the present system reliability from experimental data without attempting to fit a particular parametric curve. The estimates are usually conservative and projections on future system reliability are generally not possible. The following models provide a representative cross section of those to be found in the literature:

Model 1. This approach considered a reliability growth model in which the mean time to failure of a system with exponential life distribution is increased by removing the observed failure modes. In particular, it shows that when certain conditions hold, the increase of mean time to failure is approximately at a constant percent per trial. This is, if $\theta(i)$ is the mean time to failure of the system at trial i then $\theta(i)$ may be approximated under certain conditions by

$$\theta(i) = Ae^{Ci}, \tag{5-1}$$

where A and C are parameters. Note that

$$\theta(i+1) = e^{C}\theta(i). \tag{5-2}$$

The maximum likelihood estimates of A and C are given.

Model 2. Another model considers a situation where the system failures are classified according to two types. The first type is termed "inherent cause" and the second type is termed "assignable cause". Inherent cause failures reflect the state-of-the art and may occur on any trial, while assignable cause failures may be eliminated by corrective action, never to appear again. The model assumed that the number of original assignable cause failures is known and that whenever one of these modes contributes a failure, the mode is removed permanently from the system. This approach uses a Markov-chain approach to derive the reliability of the system at the n-th trial when the failure probabilities are known.

Model 3. This model considered the suitability of the Gompertz equation.

$$R = ab^{c^t}, \tag{5-3}$$

$0 < b < 1$, $0 < c < 1$, for reliability growth. In this equation, a is the upper limit approached by the reliability R as the development time $t \to \infty$. The parameters a, b and c are unknown. Techniques for estimates of these parameters are demonstrated by examples showing application of this model.

Model 4. This model considers a deterministic approach to reliability growth modeling (Duane Model). The approach uses data available for several systems in an effort to determine if any systematic changes in reliability improvement occurred during the development programs for these systems. Analysis revealed that for these systems, the cumulative failure rate versus cumulative operating hours fell close to a straight line when plotted on log-log paper. The cumulative failure rate appeared to decrease operating hours.

The types of systems investigated were of the complex electromechanical nature. The conclusion was that a line with a slope of -0.5 representing cumulative failure rate as a function of cumulative operating hours on log-log paper would probably be suitable for reflecting reliability growth for similar type systems.

Mathematically, the failure rate equation may be expressed by

$$\lambda(T) = KT^{-\alpha} \qquad (5\text{-}4)$$

$K < 0$, $0 \leq \alpha \leq 1$, where $\lambda(T)$ is the cumulative failure rate of the system at operating time T, and K and α are parameters. It follows then that

$$\lambda(T) = \frac{E(T)}{T} \qquad (5\text{-}5)$$

where E(T) is the expected number of failures the system will experience during T hours of operation. This yields

$$E(T) = KT^{1-\alpha} \tag{5-6}$$

Furthermore, the instantaneous failure rate at T is given by

$$\theta(T) = (1-\alpha)\ KT^{-\alpha} \tag{5-7}$$

For a system with a constant failure rate that mean time between failure (MTBF) of the system at operating time T is

$$M(T) = \left[\theta(T)\right]^{-1} = \left[(1-\alpha)K\right]^{-1}T^{\alpha}. \tag{5-8}$$

That is the change in system MTBF during development is proportional to T^{α}.
With this notation $\alpha = 0.5$ closely represented the types of systems considered.
<u>Model 5</u>. Another model considered a Bayesian reliability growth model for a system undergoing development. The parameters of the model are assumed to be random variables with appropriate prior distribution functions. Using these results, one may project the system reliability to any time after the start of the development program without data and, also, estimate the system reliability after data have been observed. The model further gives precision statements regarding the projection and estimation.
<u>Model 6</u>. This model considers a reliability growth model which assumes that a system is being modified at successive stages of development. At state i, the system reliability (probability of success) is P_i. The model of reliability growth under which one obtains the maximum likelihood estimation of P_1, P_2, ..., P_k assumes that

$$P_1 \le P_2 \le \dots \le P_K.$$

That is, it is required that the system reliability be not degraded from state-to-state of development. No particular mathematical form of growth is imposed on the reliability.

In order to obtain a conservative lower confidence bound on P_K, it suffices to require only that

$$P_K \geq \max_{i < K} P_i$$

That is, it is only necessary that the reliability in the latest stage of development be at least as high as that achieved earlier in the development program.

Data consist of x_i, successes in n_i trials in stage i, $i = 1, \ldots, K$.

Model 7. Another reliability growth model assumed that at stage i of development the distribution of system life length is F_i. The model of reliability growth under which the maximum likelihood estimates of $F_1(t), F_2(t) \ldots F_K(t)$ are obtained writing

$$F_i(t) = 1 - F_i\ (t) \tag{5-9}$$

is

$$\bar{F}_1\ (t) \leq \bar{F}_2\ (t) \leq \ldots \leq \bar{F}_K(t)$$

for a fixed $t \geq 0$. In order to obtain a conservative upper confidence curve on $F_K(t)$ and thereby, a conservative lower confidence curve on $\bar{F}_K(t)$ for all non-negative values on t, it suffices only to require that

$$\bar{F}_K(t) \geq \max_{i < K} \bar{F}_i(t)$$

for all $t \geq 0$. That is, the probability of system survival beyond any time t in the latest stage of development is at least as high as that achieved earlier in the development program.

Data consist of independent life length observations

$X_{i1}, \ldots X_{in_i}$, $i = 1, \ldots, K$

By far the model that has generated the greatest interest is the Duane model developed by General Electric (Model 4). With minor modifications this model can be tailored for helicopter development improvement programs. This model can reflect development growth testing as well as product improvement efforts. Four parameters are required to define reliability growth using the Duane model.

1. The entrance point (off the board reliability).
2. The rate of growth.
3. The inherent reliability (or the reliability at maturity).
4. The time scale used in the model.

In addition to the above a differentiation is made for the growth rate during the early development and product improvement cycle (Figure 5-1). A separate entrance point for introduction into service is also defined.

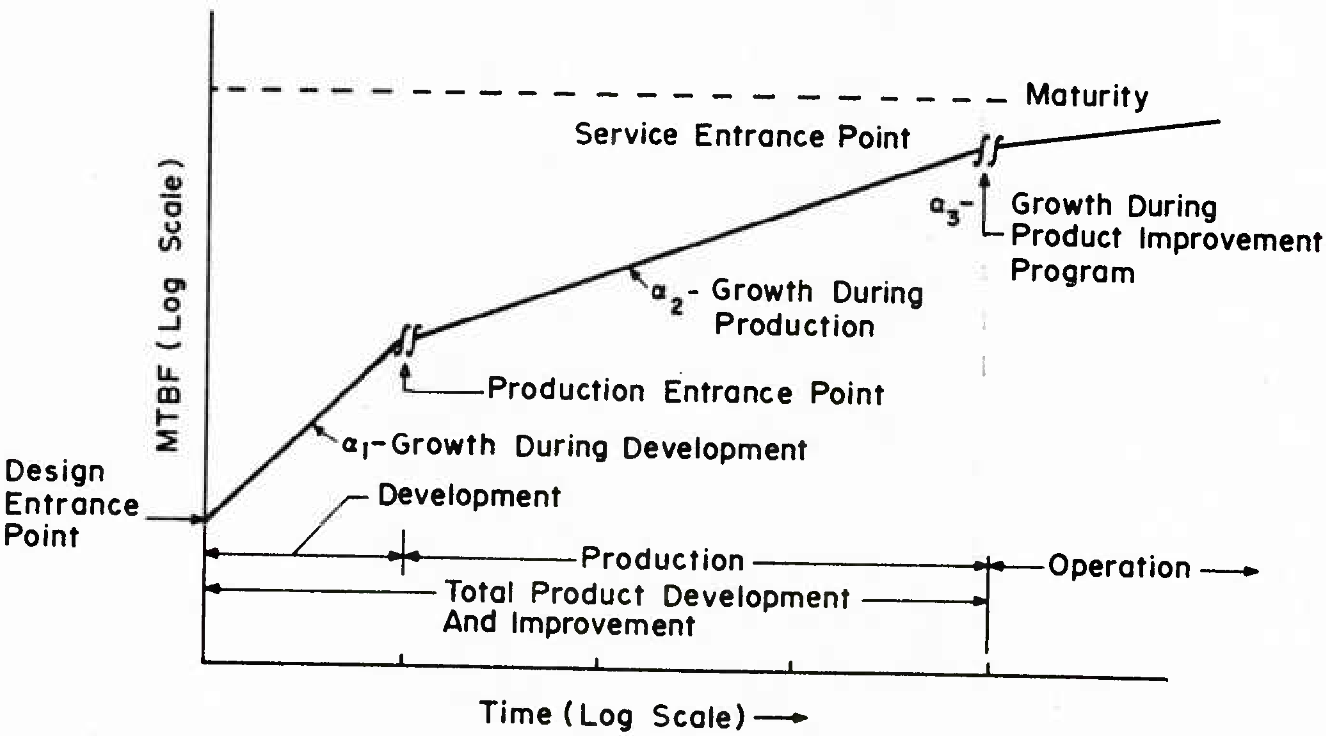


Figure 5-1 CONCEPTUAL RELIABILITY GROWTH MODEL

5.2 Reliability Growth During Development

As stated earlier, the purpose of a growth process is to achieve high reliability in field use. High reliability is dependent on the extent to which testing and other product improvement techniques have been used during development to "force-out" design and manufacturing flaws, and on the rigor with which these flaws are analyzed and corrected. A primary objective of growth testing is to provide methods by which hardware reliability development can be dimensioned, disciplined and managed as an integral part of product development. Other objectives of reliability growth testing are to:

- provide a technique for extrapolating current reliability status to some future result,
- provide methods to assess the magnitude of the test-fix-retest effort prior to the start of development, thus allowing trade-off decision.

In order to structure a growth test program for a newly designed system or major component item, a detailed test plan must first be prepared. This plan must describe the test-fix-retest concept and show how it will be applied to the system or component item under development. The plan must incorporate the following:

1. Specified and predicted (inherent) reliabilities and methods for predicting reliability (model, data base, etc.) must be described.
2. Criteria for reliability starting points, i.e., criteria for estimating the reliability of initial production hardware, must be determined.
3. Test, fix, retest conditions, requirements and criteria, as they relate to and impact the reliability growth rates, must be defined.
4. Calendar time efficiency factors, which define the relationship of test time, corrective action time and repair time to calendar time, must be determined.

Figure 5-2 illustrates the relationships of these factors. The circled numbers refer to the four (4) factors listed above.

For many systems the line representing reliability growth is a straight line on a log-log scale. Other methods of graphically depicting reliability growth are used. For example, a linear plot of reliability versus test time is depicted in Figure 5-3. Similarly, reliability growth can be expressed in reciprocal units, that is, the reduction in unreliability can be expressed as a function of time per Figure 5-4.

Each of the four factors defined above affects the reliability growth graph significantly.

Inherent reliability represents the value of reliability established by the design, and which may correspond to the value specified in procurement documents. Ordinarily, the contract specified value of reliability is somewhat less than the inherent value. The relationship of the inherent (or specified) reliability to the starting point greatly influences the total test time.

Starting point represents an initial value of reliability usually within the range of 10-40% of the inherent reliability. Estimates of the starting point can be derived from prior experience or are based on percentages of the estimated inherent reliability. Starting points must take into account the intensity of the R&M design program and the relationship of the system under development to the state-of-the-art. Higher starting points minimize test time.

Rate of growth represented by the slope of the growth curve which is, in turn, influenced by the rigor and efficiency by which failures are discovered, analyzed and by which correction action is implemented into test hardware. Rigorous test programs which foster the discovery of failures, coupled with management supported analysis and timely corrective action, will result in a faster growth rate and consequently less total test time.

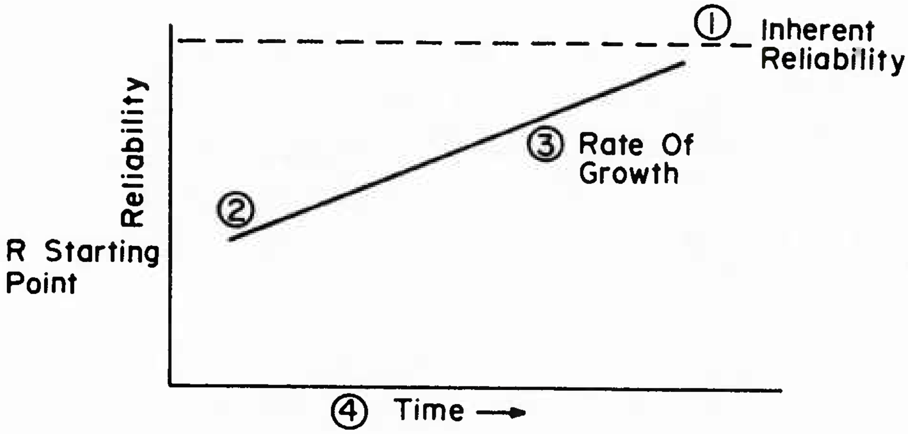


Figure 5-2 RELIABILITY GROWTH PLOT - LOG-LOG SCALE [1]

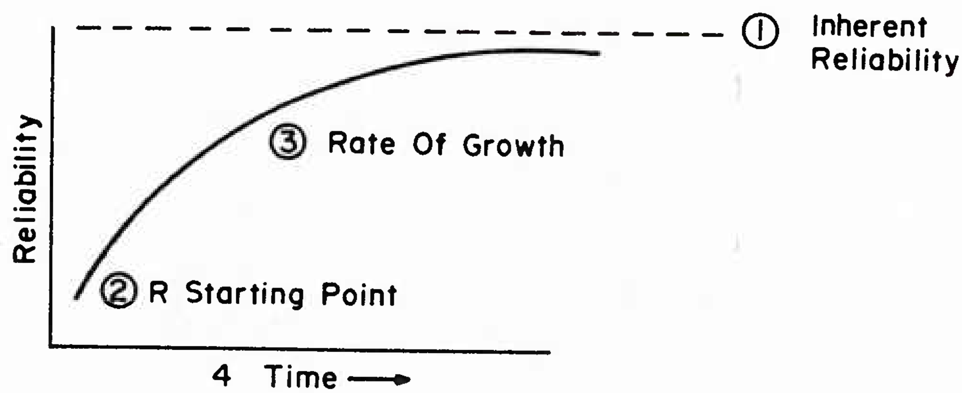


Figure 5-3 RELIABILITY GROWTH PLOT - LINEAR SCALE [1]

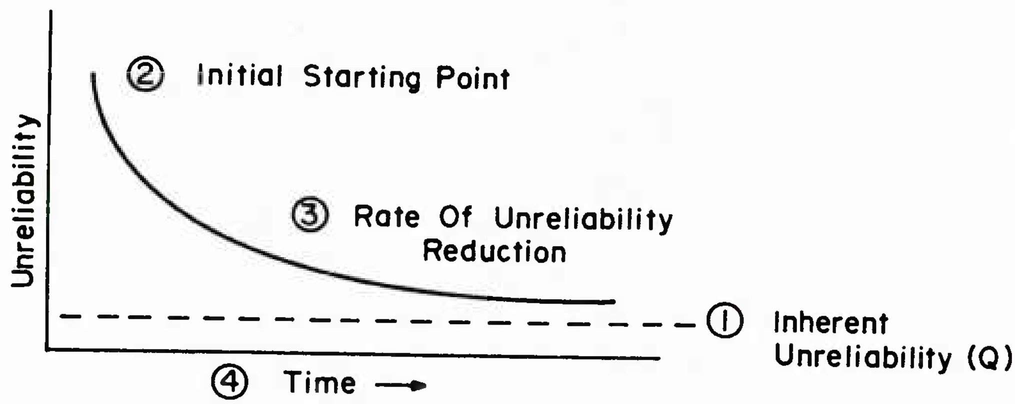


Figure 5-4 RELIABILITY GROWTH PLOT - INVERSE SCALE [1]

Calendar time/test time represents the efficiency factors associated with the growth test program. Efficiency consideration included repair time, operating/non-operating time as they relate to calendar time. Lengthy delays for failure analysis, implementation of corrective action or short operating periods will extend the growth test period.

Each of the four factors impacts the total time (or resources) scheduled to grow reliability to the specified value. To optimize the reliability of a helicopter system or component item, specific and detailed allocation and trade-off analyses must be made with respect to these factors and fixed budgeting constraints.

5.3 Reliability Growth During Production

Reliability growth, in the context of production reliability degradation, is a measure of success in the removal of manufacturing flaws which inhibit post production reliability from matching inherent design reliability. The basic concept associated with production reliability growth involves consideration of production processes for detecting and rejecting defects and re-inspection and retest. Specifically, production reliability growth is an iterative inspect and test-reject-correct process. As previously indicated, there are three essential elements involved in achieving production reliability growth:

1. Detection and rejection of defects.
2. Analysis and improvement of production processes.
3. Continuing inspection and testing.

The rate of reliability growth depends on how rapidly these three elements can be accomplished, the efficiency of the inspection and test processes and the effectiveness of process improvements. As indicated in Figure 1-3, at the initiation of the production phase, a decrease in reliability is characteristic, due primarily to workmanship errors resulting from unfamiliar operations and immature production processes. As production continues, skill increases and reject analysis drives process improvements causing production reliability to approach the inherent (design based) value.

Process improvements are accelerated by inspection and test procedures which provide an early indication of manufacturing problems. Manufacturing learning is enhanced by reject analysis and accelerates the reduction of defects induced in the manufacturing process. Inspection efficiency may be characterized by inspector performance and the number of serial inspections in the production flow. Figure 5-5 presents a conceptual performance curve for an inspector throughout the production program.

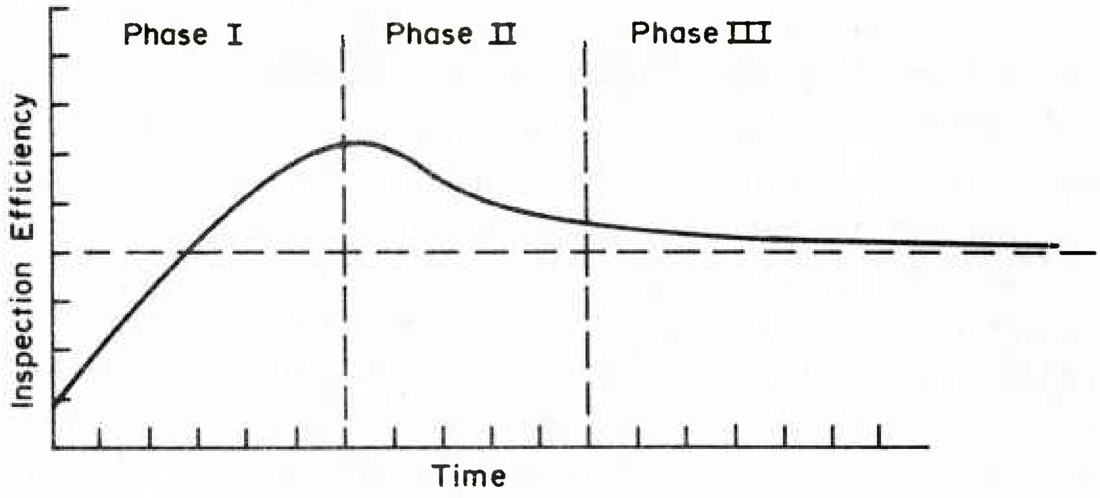


Figure 5-5 INSPECTION EFFICIENCY AS A FUNCTION OF MANUFACTURING MATURITY.

As production gets under way, a period of learning is experienced during which inspection efficiency grows, the rate of growth depending on inspector past experience (Phase I). After procedures have been well established and the inspection process has become routine, a second phase may be identified during which human performance factors, such as boredom, become apparent and degrade inspection efficiency. Finally, an efficiency level is established at which negative human factors are balanced by positive attitudes to achieve an acceptable degree of job performance. This level is indicated by Phase III in which inspection efficiency remains relatively constant.

Knowledge of the characteristics of this time varying efficiency allows techniques of human engineering to be applied to their correction and identifies weaknesses which must be corrected to promote reliability growth. Such techniques may encompass concepts such as use of less experienced inspectors after the inspection process has become perfected (Phase II) to alleviate boredom. Incentive programs may be initiated in Phase III to upgrade efficiency levels or inspection stations rotated to restimulate interest.

The power of multiple inspections in increasing overall efficiency is shown in Figure 5-6 where, for example, a single inspection with an efficiency (.6) can be increased to over (.8) by addition of a second inspection. When production processes are new the inspection efficiency will in general be lower than it will be as the production process and inspection process matures. The use of multiple inspection on new processes will increase the overall inspection efficiency and provide information which will increase inspector learning.

Figure 5-6 shows the ratio of the defects coming into an inspection to the defects leaving the inspection as a function of inspection efficiency and number of inspections.

Figure 5-7 may be used to estimate the point of diminishing returns achieved through increased inspections. A cost effectiveness analysis of increased inspections must incorporate consideration of other methods of enhancing reliability growth. Trade-offs may be made between process improvements, additional or improved screen testing as well as additional or improved inspection techniques. The effectiveness of any of these growth enhancement techniques may be assessed through exercise of the production degradation model discussed in Section 3. The incorporation of cost with these process improvement techniques allows selection of optimum cost effective improvements. The measurement of reliability growth requires observable variables which change with process alteration. Inspection efficiency and reject rate are applicable variables to assess growth of production reliability. If the efficiencies remain constant a reduced reject rate indicates process improvement. If the process is not altered, an increased reject rate indicates an improvement in inspection efficiency. To assess the impact of such process alterations, the production degradation procedure may be applied by first updating the production flow chart to reflect alterations in the process and proceeding to apply the procedure described in Section 3.2. Exercising the procedure to obtain output MTBF and comparing with the inherent value provides a measure of reliability growth achieveable through process improvements.

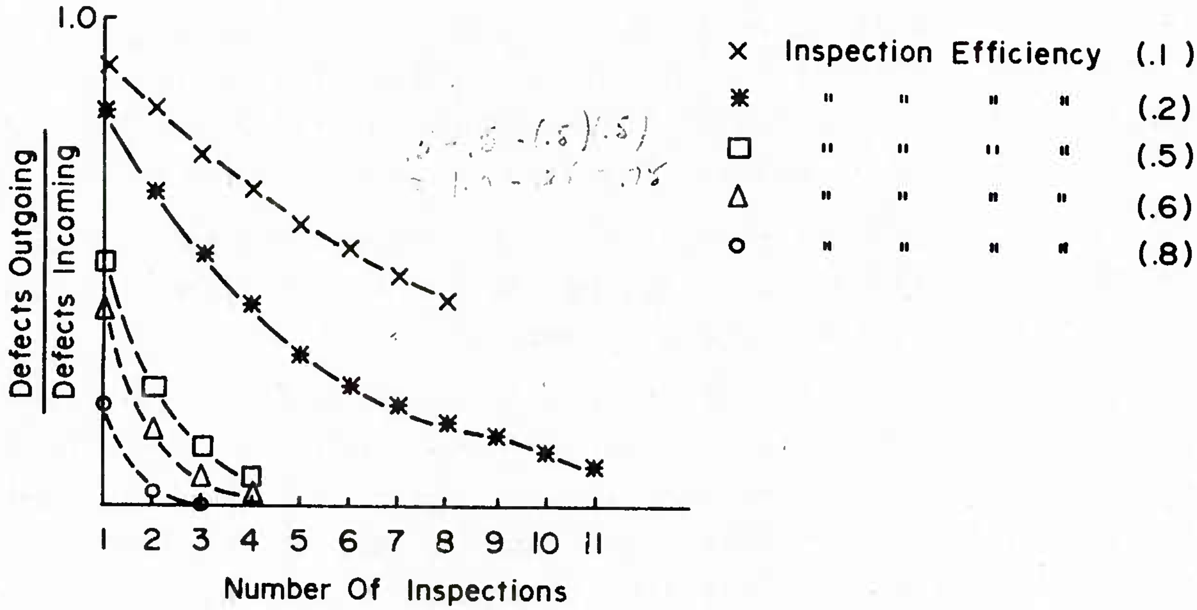


Figure 5-6 EFFECT OF MULTIPLE INSPECTION ON DEFECTS

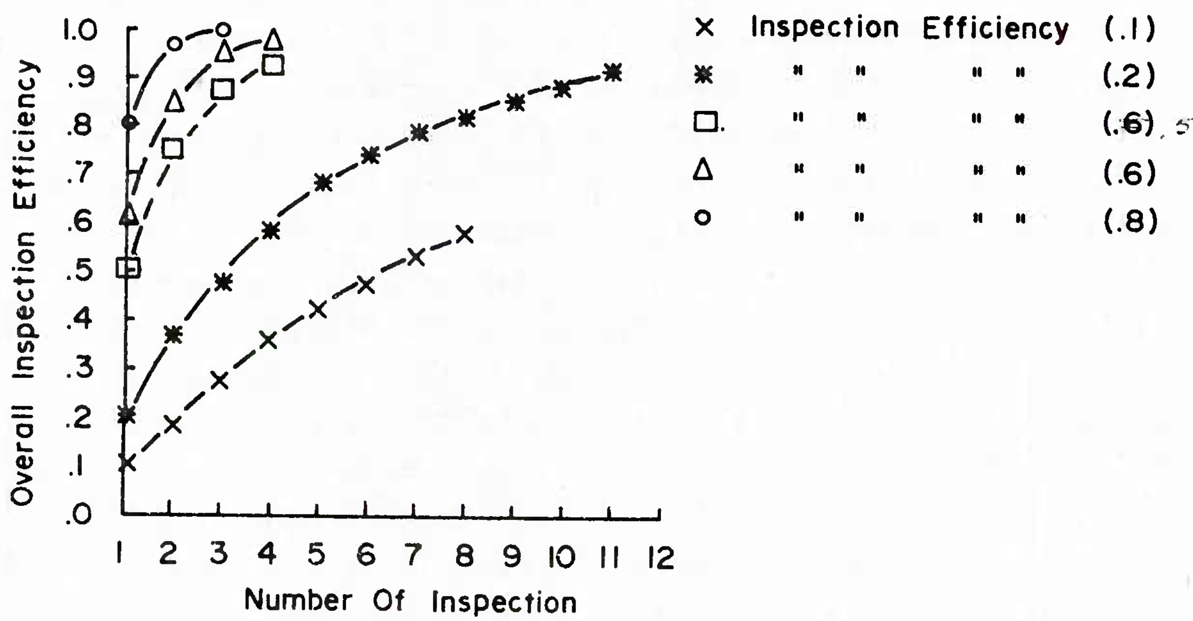


Figure 5-7 EFFECT OF MULTIPLE INSPECTION ON OVERALL INSPECTION EFFICIENCY.

The following example applies the technique discussed above to illustrate the degree of reliability growth achieveable through process modifications which reduce defects and improve inspection efficiencies.

Reliability Growth Example

Consider again the manufacture of a roller bearing (see Example 2 of Section 4). The production flow diagram for the manufacturing process is depicted in Figure 4-4 . The degradation factor calculated for the bearing in Example 2 is .0233 indicating that the output MTBF must be increased by about 98% to achieve the inherent value.

To illustrate how production reliability may be made to grow toward this value, the following production improvement scheme is presented:

1. The torque test at the end of the production flow is an operational test presently having a defect conversion efficiency of $S = .65$ and a detection efficiency of $I = .9$. Table 3-4 suggests a range of .38 to .98 for defect conversion efficiency. Assume that through improved test equipment costing $1000 and updated procedures, the conversion efficiency is raised to $S = .85$. Revising the process diagram to reflect this change and repeating the mathematical operation, the resultant defect rate is found to drop from $L = .174$ to $L = .099$.

2. Quality defects caused by the cutting process are induced at the rate of 10 per 100 operations. Assume that through improved maintenance of the cutting equipment this defect rate may be reduced to 5 defects per 100 operations. The increase in maintenance costs over the production contract period is $4000. Assessment of this change is made by updating the process flow diagram and recalculating output defect rates. The impact of this improvement is observed as a reduction in output quality defects from $Q = .087$ to $Q = .077$.

3. The finish and dimension inspection is a composite of two distinct inspections. Table 3-3 indicates a range of .4 to .9 for visual inspections and a range of .4 to .9 for microscopic inspections. In the original production flow, an efficiency of E = .8 was assumed for each, resulting in a combined efficiency of .64. Assume that through inspector learning, each efficiency factor increases to E = .85, resulting in a combined efficiency of .72. This is a no cost improvement expected to occur as the production process matures. The adjustments are made to the process and calculations indicate this change in inspection efficiency decreases the output quality defect rate from Q = .077 to Q = .067.

4. Assume that through manufacturing learning, and better control of processes, the assembly process induces 5 latent defects per 100 operations instead of the previous 10 defects per 100 operations experienced at the beginning of production. This is a no cost improvement expected to occur as the production process matures. The updated process defect rates are entered into the calculation indicating a reduction in induced latent defects. The result is a drop in output latent defects from L=.099 to L=.087.

5. Finally, an additional operational test and final inspection is devised to reduce remaining defects to an acceptable level. The operational test conversion efficiency is .9 and the detection efficiency is .9. The cost of the additional test equipment and operators over the production process period is $80,000. The final inspection efficiency is also maintained at .9 by using experienced inspectors and an incentive plan costing $20,000 over the life of the contract. The final outgoing quality and latent defect rates are Q = .007 and L = .016. A summarization of the production improvements leading to reliability growth, their impact on output defect rates, percent improvement, cost effectiveness and calendar time of implementation is given in Table 5-1.

Table 5-1 RELIABILITY GROWTH SUMMARY

Improvement Technique	Calendar Time (Days)	Parameter Changed	Magnitude Of Change	Output Defect Rate		Reliability Degradation Factor	Cost Effectiveness Percent Improvement Per Dollar
				Q	L		
Beginning of Production	0-10	—	—	.087	.174	.0233	—
1. Improve Torque Test Efficiency	16	S	.65 to .85	.087	.099	.0326	.0400
2. Improve Cutting Process	21	q	.10 to .05	.077	.099	.0386	.0165
3. Improve Efficiency of Finish and Dimension Inspection	23	E	.64 to .85	.067	.099	.0410	—
4. Improve Assembly Process	25	ℓ	.10 to .05	.067	.087	.0442	—
5. Additional Operational Test and Final Inspection	365	—	—	.007	.016	.2957	.0117

The reliability growth derived from the process changes discussed previously, is evident in the growth plot illustrated in Figure 5-8.

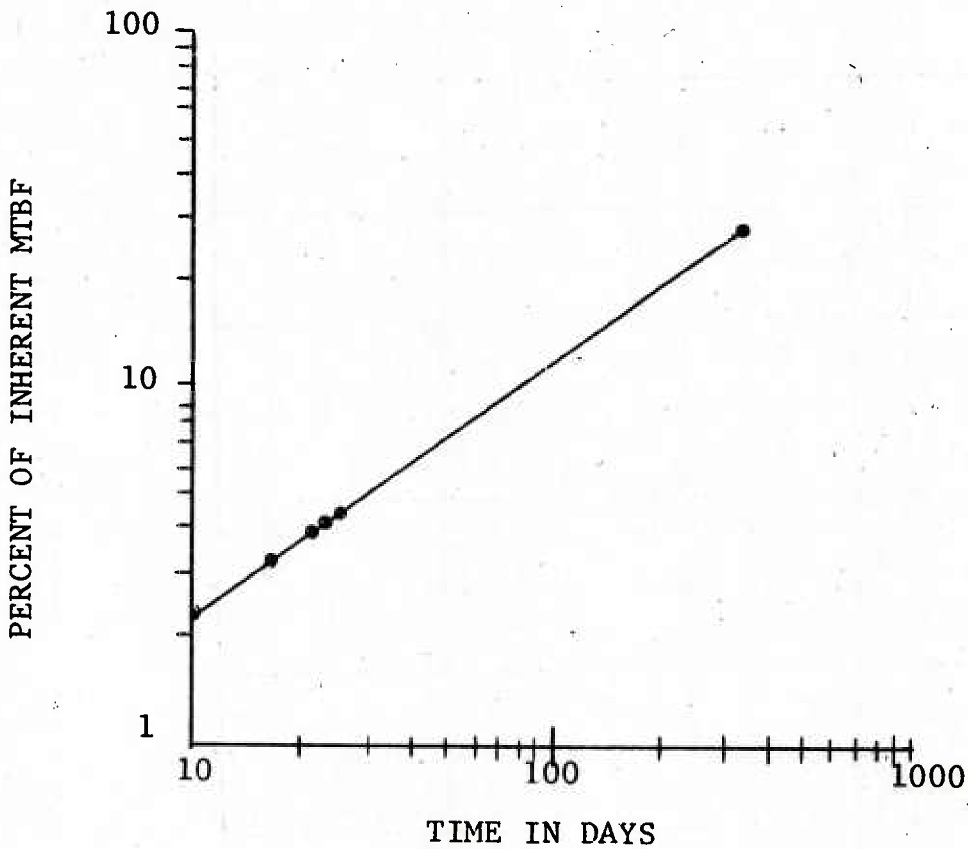


Figure 5-8 RELIABILITY GROWTH

6.0 CONCLUSIONS AND RECOMMENDATIONS

An overall methodology has been developed that can be used to predict, improve and control the reliability of helicopter system and components. Included as part of the methodology is a detailed procedure to evaluate quantitatively the impact of production on reliability and in particular the early failures and defects that give rise to infant mortality and account for the reliability and quality degradation due to manufacturing. A rigorous mathematical theory derived from basic probability considerations of specific production processes was presented as the background from which the reliability assessment tool was formulated. Gross data, collected from the helicopter industry, was tabulated into a format allowing direct input to the model. A step-by-step procedure was presented and its usefulness demonstrated by application to several examples. The procedure was formulated in a format permitting use of the assessment technique whether significant historical data is available, data is collected from an on-going process, or if data from the specific process of interest was totally nonexistent. The value of the model, regardless of the data base, was discussed in terms of its use in identifying factors which promote reliability growth in the production process.

Examples presented in this report have proved the validity of the methodology to assess production reliability degradation and to foster reliability growth prior to field release but as well, have brought to bear the significance of, and the need for a viable data base. A data base is needed from which to draw the detailed information influencing reliability of the design as well as the manufacturing processes. Also required are assembly and inspection techniques as they would apply to helicopter systems and components.

Based on the value of such a data base, and the fact that a coordinated effort to methodically collect such data is nonexistent, the following recommendations are presented.

1. Development of a Data Center

Development of a data center dedicated to the collection of documents, papers, specification, procedures, numerical data and other information pertaining to aircraft (especially helicopters) would significantly enhance evaluation of production reliability degradation. Particular types of information to be collected include:

- Material and part design reliability data (failure rate).
- Material, part and component fabrication methods and impact of production environment on them.
- Inspection techniques and data defining inspection efficiency.
- Reject rates and kinds of rejects found by various inspection methods.
- Stress data and kinds of tests employed, efficiencies, costs and ease of implementation.

A detailed plan for the establishment of an on-going data analysis center that is dedicated to provide such data was developed as part of the study. This plan is presented in Appendix B and includes

(a) the objective and scope of the center

(b) an implementation plan

(c) general organizational requirements

(d) specific functional outputs of the center.

2. Computerization of the Model

Conversion of the methodology into a computerized technique adds the facility of performing rapid trade-off analyses. Having applied the methodology to estimate out-going from production reliability, the problem remains of identification of the basic parts or materials and/or production processes which must be altered or added to implement reliability growth. The selection of cost effective changes requires sensitivity analysis studies most effectively performed by a computerized analysis model.

3. Preparation of a Handbook

The most effective application of the methodology and the computerized assessment technique would be enhanced by the preparation of a handbook dedicated to such topics as the following:

- Step-by-step instructions for performing a reliability assessment during production (manually or by automated methods).
- Details of the model which account for process induced defects and inspection efficiency.
- Comprehensive data tables covering design, manufacturing processes and the kinds of failures and defects induced.
- Inspection methods and their efficiency.
- Types of stress testing currently used to uncover latent defects.

It is anticipated that implementation of the above recommendations will facilitate the continuing development of reliability prediction and growth modeling described in this report and culminate in standardized techniques and data bases similar to those currently applied by the user community to the assessment of inherent (design) reliability.

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APPENDIX A

DEFECT CONTRIBUTIONS TO INFANT MORTALITY

APPENDIX A

DEFECT CONTRIBUTIONS TO INFANT MORTALITY

In Section 1.1, a discussion of the life characteristic curve was presented. In that discussion, particular emphasis was placed on the infant mortality region which was described as a composite of three separate failure components. This region and its constituent components are illustrated in Figure A-1 below, derived from Figure 1.1 of Section 1.

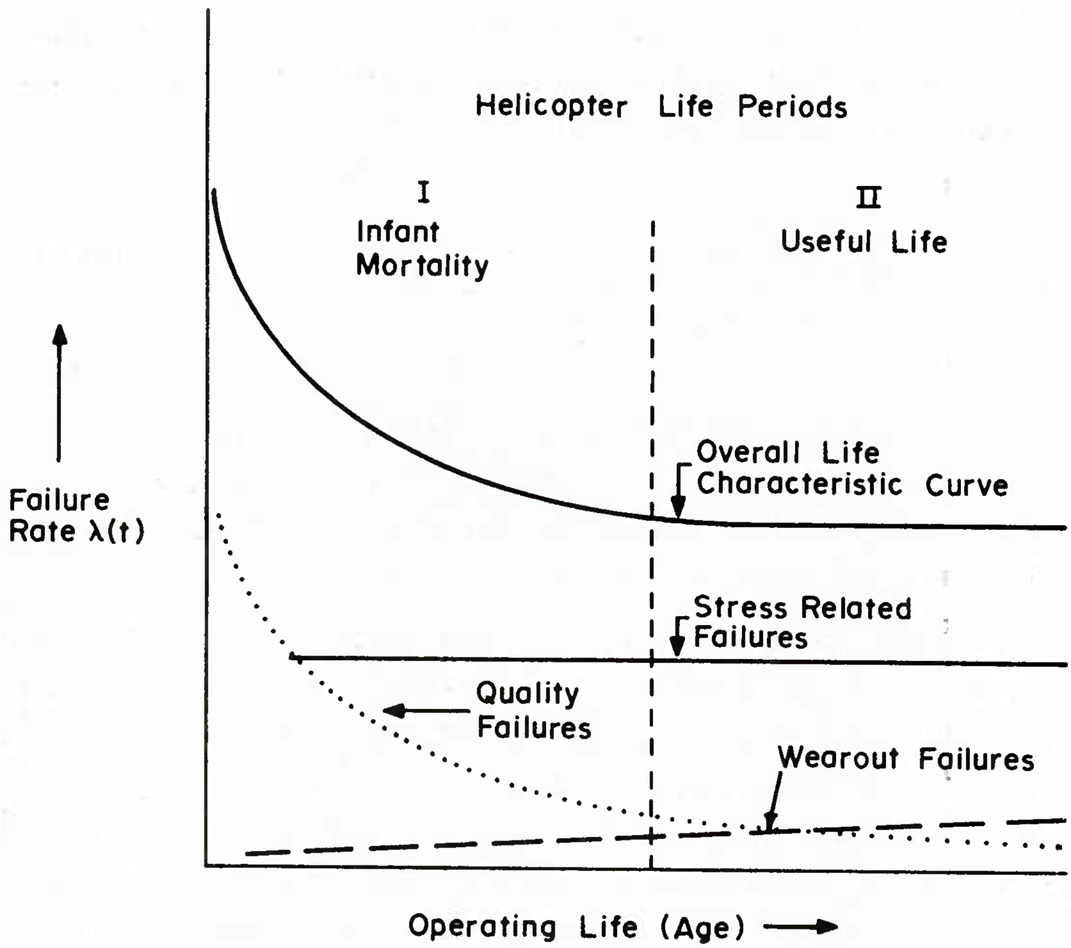

Figure A-1 Components of Failure (Infant Mortality)

If these components are reexpressed in terms of hazard rates and assumed to consist of, a constant high quality hazard component, a constant latent hazard component and a negligible wearout hazard component, failure rate may be replaced by hazard rate. The resulting impact on the life characteristic curve for the infant mortality region will be deduced from the following.

The hazard function is defined as:

$$Z(t) = \frac{f(t)}{R(t)} \tag{A-1}$$

where

$f(t) = \lambda e^{-\lambda t}$, the failure density function

$R(t) = \int_t^\infty f(t)dt$

$t = $ time

Assuming an exponential failure density for both quality and latent components, the hazard function during the infant mortality period may be expressed as:

$$Z(t) = \frac{\lambda_Q e^{-\lambda_Q t} P(Q) + \lambda_L e^{-\lambda_L t} P(L)}{e^{-\lambda_Q t} P(Q) + e^{-\lambda_L t} P(L)} \tag{A-2}$$

where

λ = failure rate for a unit with a quality defect

λ = failure rate for a unit with a latent defect

$P(Q)$ = probability a unit contains a quality defect

$P(L)$ = probability a unit contains a latent defect.

In general, manufacturing induced defects reduce a unit's strength and cause the unit tp fail prematurely. The size of the defect will determine the extent of the reduction of the part strength. Since a quality defect is observable without loading and a latent defect is not detectable unless loading is applied, it is reasonable to assume that the strength reduction due to a quality defect is greater than the strength reduction due to a latent defect. This implies the following relation between the failure rates due to quality and latent defects:

$$\lambda_Q = k\lambda_L \tag{A-3}$$

where $k > 1$.

Substituting Eq. (A-3) into Eq. (A-2),

$$Z(t) = L \frac{ke^{-\lambda_L t(k-1)} P(Q) + P(L)}{e^{-\lambda_L t(k-1)} P(Q) + P(L)} \tag{A-4}$$

Immediately following start of production ($t = 0$), the hazard rate is relatively high,

$$Z(0) = \lambda_L \quad k\ P(Q) + P(L)$$

Since $k > 1$, it follows that

$$Z(0) > \lambda_L \tag{A-5}$$

For time greater than the infant mortality period, ($t \rightarrow \infty$),

$$Z(\infty) = \lambda_L$$

For times during the infant mortality period, $0 < t < \infty$, Eq. (A-2) has a general exponentially decaying characteristic. Conceptually, the shape of the hazard function during the infant mortality period as predicted by Eq. (A-4) is as shown in Figure A-2 and is in general agreement with the infant mortality region depicted in Figure A-1.

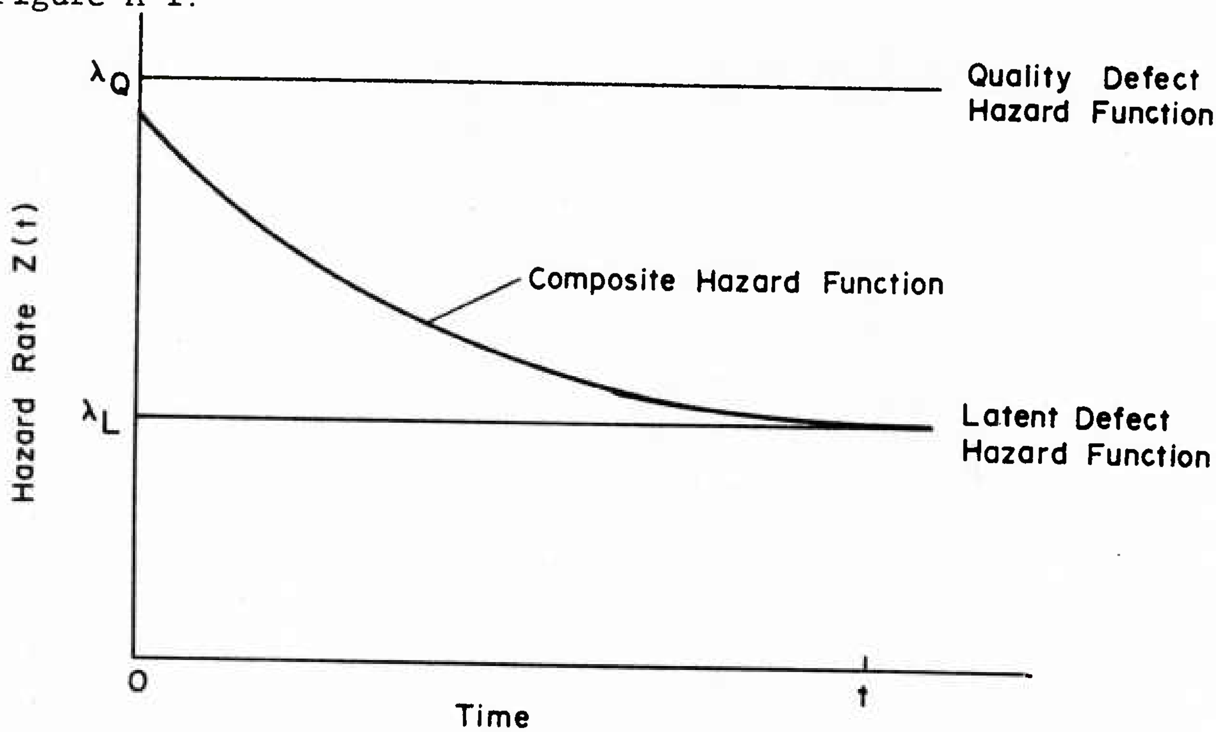

Figure A-2 PREDICTED INFANT MORTALITY HAZARD FUNCTION

It is of further interest to assess the impact of reducing quality defects on the hazard function. As quality defects are removed (by efficient inspection) or prevented from being induced (by process improvements), the general response on the hazard rate, as predicted by Eq. (A-4), is as depicted in Figure A-3.

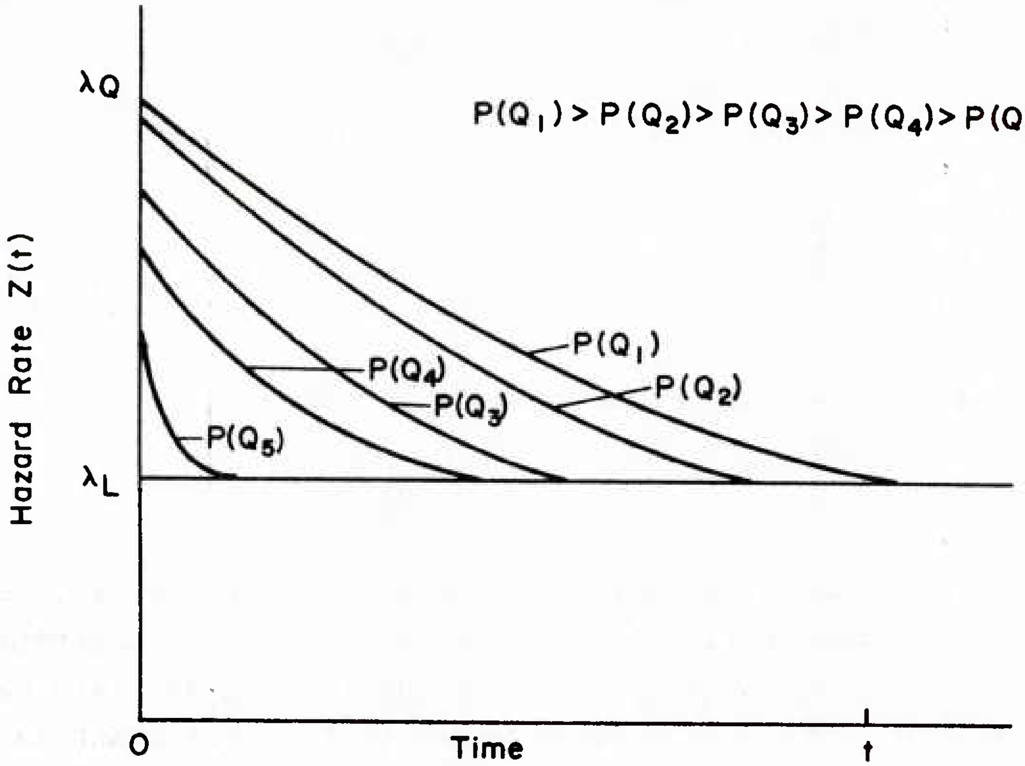

Figure A-3 AFFECT OF REMOVING QUALITY DEFECTS ON HAZARD RATE

In the limit as $P(Q) \rightarrow 0$ the hazard function $Z(t) \rightarrow \lambda_L$.

A P P E N D I X B

ESTABLISHMENT OF AN
ON-GOING RELIABILITY DATA ANALYSIS CENTER

TABLE OF CONTENTS

LIST OF FIGURES

1.0 INTRODUCTION

The findings of the investigative efforts performed under this study have indicated that a reliability prediction growth and control model based on collected, reduced and analyzed part data as well as process defect and inspection efficiency data is feasible and practical. The study has indicated that the reliability of helicopter systems can be described by their parts and materials as well as the processes and inspections necessary for their manufacture. Furthermore, these parts, materials, processes and inspections can be classified into a manageable number of generic categories suitable for data collection and analysis efforts.

In order to meet the needs of the reliability model, specific data items relative to the generic categories must be compiled, analyzed and reduced. Such data items include:

- Material and part design reliability data (failure rate)
- Material, part and component fabrication methods and impact of production improvement on them
- Inspection techniques and data defining inspection efficiency
- Reject rates and kinds of rejects found by various inspection methods
- Stress data and kinds of test employed, efficiencies, cost and ease of implementation

Since, present field data collection techniques accumulate and reduce records on a level of assembly to high to establish part failure rates, process defect rates and inspection efficiencies, and since only a fraction of helicopter components are listed and classified in conventional reliability data sources (FARADA[1], GIDEP[2], NON-EL R HDBK[3]), AVSCOM requested that details

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[1]Failure Rate Data (FARADA) Program, Fleet Missle Systems Analysis and Evaluation Group Annex, Naval Weapons Station, Seal Beach, Corona, California.

[2]Government and Industry Data Exchange Program (GIDEP).

[3]Cottrell, D. F., et al, "Nonelectronic Reliability Notebook", Marten Marietta Aerospace, Oct., 1974.

pertaining to the establishment of a full reliability information and analysis center be investigated as part of the study program. The intent was to fully define the make-up of a dedicated reliability data analysis center, which could be incorporated into AVSCOM's present data collection functional activities, that provides;

- Specific data items, including statistical as well as parametric, that are needed to implement the reliability prediction, growth and control model.
- A common data base (that is continuously augmented) which can be used to compare and assess contractor predictions and growth efforts as well as serve the total "user community" responsible for upgrading and controlling component and system reliability.

This appendix provides a plan for the establishment of such a center.

It should be emphasized that, in order to have an effective and viable methodology and data base that fully accomplishes the overall objectives of reliablity prediction and growth, the analysis technique should relate engineering variables (the language of the designer and stress analyst) to reliability measures (the language of program managers and contractual documentation). The technique should be detailed enough to relate to design and production variables and be general enough to apply to the generic classes of helicopter parts, components, processes and inspections. Furthermore, it should be easy to apply and should be easily communicated to management.

Accomplishment of the above objectives requires the compilation and analysis of both controlled test data and field data.

- Stress levels are known.
- Time to failure is recorded.
- Failure modes are identified.

Controlled test data does not represent actual field conditions. Controlled test data does, however, offer the most direct approach to obtain the relationships between engineering and reliability variables. Field data, on the other hand, has the following attributes:

- Failure modes are broadly identified or unknown.
- Fleet flying hours are approximated.
- Stress levels and environment are unknown.

Field data does, however, reflect the gross reliability experience of hardware operating in the field environment.

The approach to data analysis and reduction, relative to this reliability data center investigation, is to use control test data to derive relationships between design, production and in general generic reliability factors and then to adjust the estimates to predict field reliability based on broad adjustment factors that can be derived from the field data. The controlled test data can be obtained from:

- Helicopter and engine manufacturers
- Part, material and component suppliers (bearings, seals, pumps, etc.).
- AVSCOM quality test programs
- Controlled army test programs (Lead The Fleet, etc.)
- Other military and non-military sources willing to share and pool their test data

The field data would be obtained from:

- TAERS/TAMMS (as analyzed and reduced by RAMMIT)
- GIDEPS - FARADA
- 3M (NAVY)
- 66-1 (AIR FORCE)

The following sections of this appendix describes implementation and organization details pertaining to the establishment of an on-going reliability data analysis center. Included are:

(a) The objective and scope of the center (Section 2.0)
(b) An implementation plan (Section 3.0)
(c) General organizational requirements (Section 4.0)
(d) Functional outputs (Section 5.0)
(e) Input requirements (Section 6.0)

2.0 BROAD OBJECTIVES & SCOPE OF THE DATA ANALYSIS CENTER

The long term objectives of the data analysis center are to improve the field reliability of Army Aviation systems and components through reduction of failures and in particular production degradation factors. While advances have been made in these objectives in recent years, it has become apparent that a number of basic factors make achievement of high reliability difficult. Among these factors are the relative absence of detailed and valid reliability data to support reliability prediction, growth and product improvement efforts.

As previously stated, the approach is to establish a centralized reliability analysis center to collect, organize, store, and disseminate specific component, material and process oriented reliability information and experience and, thus, to support the reliability model described in this report and to serve its community of users with up-to-date information not heretofore available. In addition, this accessible store of knowledge will provide guidance to existing and proposed component reliability test, hardware reliability growth and demonstration programs, and production reliability improvement programs and serve as a realistic data source in the timely up-dating of applicable Army Helicopter planning and specification documents.

The purpose of the analysis center is to acquire and disseminate reliability information with the prime objective of improving the reliability of helicopter systems and components. The means employed would be the following:

a. Collecting, reducing, correlating, analyzing and storing of reliability experience data including both design and production as previously defined and which emphasizes generic categories of parts, materials processes and inspections. These will consist of part test, development test, field test, production and operational data which is generated by governmental and industrial sources.

b. Periodically publishing current reliability information vital to all aspects of design, selection, test, production and application.

c. Providing a central point of inquiry for reliability information users.

d. Increasing the use of hardware based on parts, material and processes of established reliability.

e. Improving and standardizing on reliability testing (e.g., growth, demonstration and production testing) and reporting procedures.

f. Improving reliability specifications.

g. Identifying part and data gaps and recommending corrective action.

h. Providing guidance to part reliability test programs and reliable part development programs to maximize their effectiveness.

i. Developing and periodically updating the reliability prediction growth and control model described in this report.

j. Compiling a technical document library of Helicopter Reliability related documents and mechanical reliabliity documents for systems analysis.

In order to implement a data analysis center that meets the above objectives requires addressing the following areas:

a. Organizational structure.

b. Data base required.

c. Analysis programs for maximum utilization of the data base.

d. Query methods and query formats.

e. Types of communication.

f. Methods for publication and dissemination of data output.

g. Sources and amounts of valid data available.

h. Make-up of preferred parts, material and process lists.

i. Methods of analysis required for validation purposes.

j. Required reporting formats.

k. Controls necessary to assure the validation of reported data.

3.0 THE IMPLEMENTATION PLAN

In this section the assumptions necessary for implementation are outlined and the relationships between an on-going data analysis center (and in particular the components of the center) and the community with which it interacts is discussed.

A major underlying assumption of this special study was the fact that the center should perform the broad objectives which have been cited in Section 2.0 of this appendix with respect to helicopters and components, including all mechanical dynamic parts, production processes and inspection techniques and reliability prediction methods, within 5 years from its inception. A shorter schedule is believed to increase unduly the risk of investment in unproven and potentially less useful services, while increasing the starting costs beyond justifiable limits. A substantially longer schedule is likewise believed uneconomical; in this case the center would spend many years in a "catching-up" mode, with insufficient practical services to the user community combined with excess costs due to this stretch-out.

Figure B-1 presents relationships between the proposed center and other agencies and groups at full operation, i.e., 5 years after inception. The data base can be kept current by data inputs on a regular basis from components vendors, hardware manufacturers and appropriate sources from within the Army. Data Centers such as GIDEP-FARADA, and others could cooperate by furnishing data in such restricted categories as summarized field failure data.

The center, in turn, will furnish analyzed data to these same sources, as well as to the Army Parts Data Bank. The data can consist of established output categories designed to satisfy the particular requirements of the users. The outputs can range from part failure rates specific to a process family, to the identification of part availability gaps, parts lists of established reliability, and prepared parts and material lists under applicable specification. There can also be the capability to answer specific ad hoc inquiries.

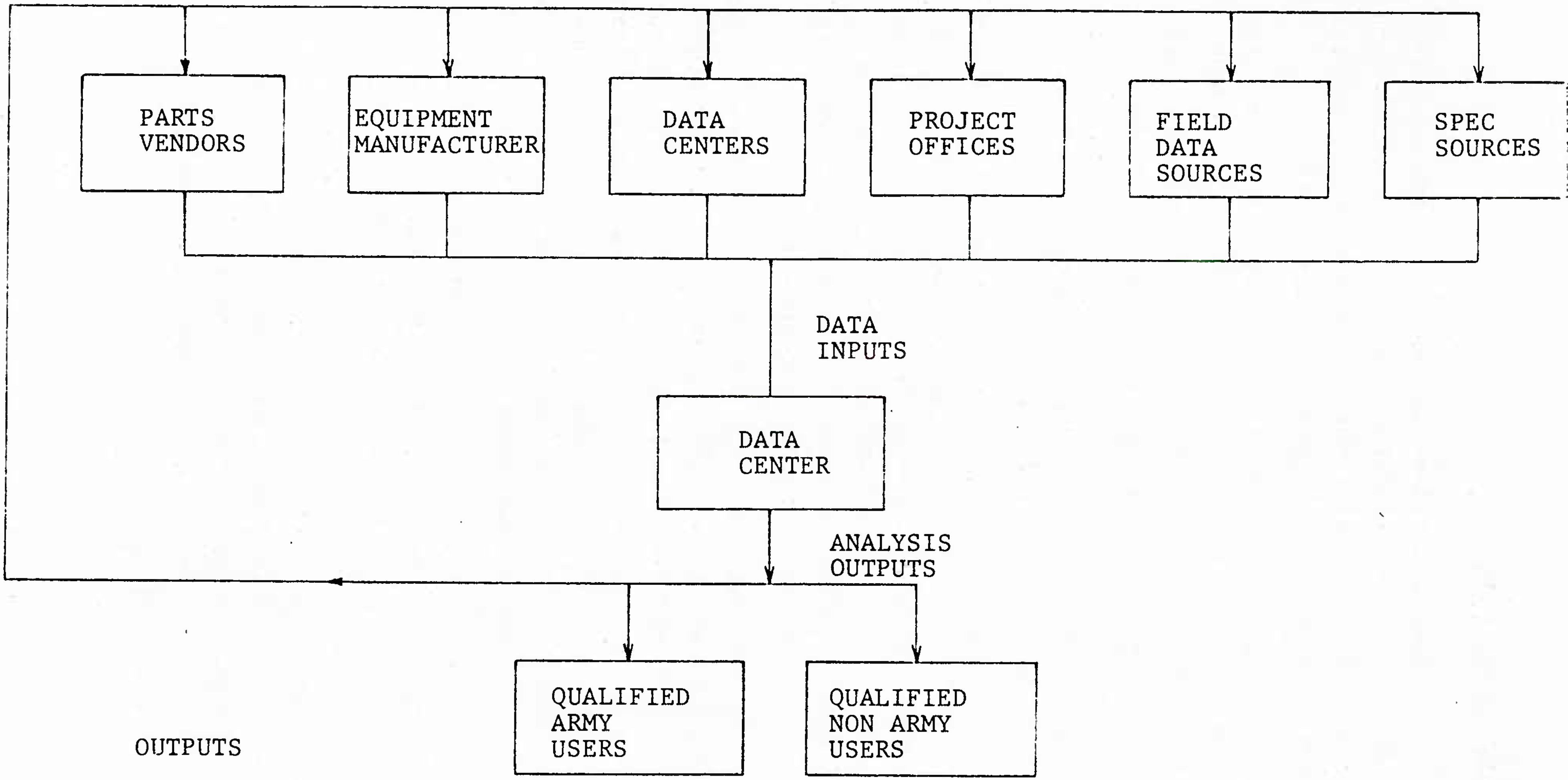


Figure B-1 DATA FLOW

In addition, the center can furnish AVSCOM with specifications and procedures, updated in a timely fashion and designed to improve its operation in particular and the reliability of procurable helicopter systems in general. Figure B-1 indicates that the center closes the loop in a reliability improvement and feedback system, acting as the controller which drives the system to improved reliability performance. This is the ultimate justification for the center, the functional flow of information through provision of specific outputs.

It is apparent that the center must, in order to meet practical constraints, perform valuable functions earlier than the proposed 5-year implementation schedule. The early factors data collection, computer programming and other starting costs must be balanced by early achievement of at least part of the eventual goals. Mileposts have been identified for this purpose as follows:

1. An initial data analysis operation that provides data based on critical parts, processes and inspection only.

2. Preparation of a Reliability and Application Handbook, containing the most urgently required analyses based on the initial data collection on the critical parts, production processes and inspections that comprise the helicopter dynamic components.

The initial data analysis operation would provide dynamic part data from early data collection efforts and from the parts and process data generated under any present helicopter improvement program. The initial scope would include parts common to the:

- Engine
- Transmission
- Drive Trains
- Rotor Systems
  - Rotor Head
  - Rotor Controls
  - Rotor Blades

for all helicopter systems.

The gross data base presented in Section 3.3 of this report would represent the starting point for the initial data collection analyses operation.

The Reliability Handbook is planned to be a by-product of the initial data analysis effort. It would be based on the procedure provided in Section 3.2 of this report. It can be prepared without the flexible computer data retrieval file that may be required for other functions of the center. It will serve the "designer" portion of the user community with an improved reference work early in the program. Specifically, it will provide analyzed critically evaluated data for:

- Reliability prediction.
- Reliability growth planning and testing
- Component selection and assessment
- Quality assurance specifications
- Failure modes and mechanism analysis
- System reliability analysis
- Reliability production analysis

In addition the intent is to develop a handbook that can be readily updated as evaluation techniques are improved and more extensive data becomes available.

A key part of the handbook would be to provide a reliability prediction procedure that can be used to establish the inherent reliability of helicopter systems and components (step 1 of the procedure presented in Section 3.2). The procedure would be based on the following premises:

- System failure is a function of part failure
- Reliability is a function of complexity
- A measure of complexity is the number and type of parts comprising the system.
- A part is defined as the lowest level of assembly where commonality exists and data can be collected (strength attributes can be derived from a parts material properties).
- Certain basic components can be treated as a part
- Basic strength-stress relationships can be derived for parts

Figure B-2 depicts conceptually how reliability (i.e., MTBF) relationships can be developed and presented as a factor of stress (i.e., vibration) for two (2) levels of component quality. Figure B-2 is a sample relationship intended to illustrate how data can be reduced and presented. It does not represent an actual MTBF vs. stress relationship. This can only be determined through detailed analysis of controlled reliability vs. stress data using probabilistic design techniques.[4]

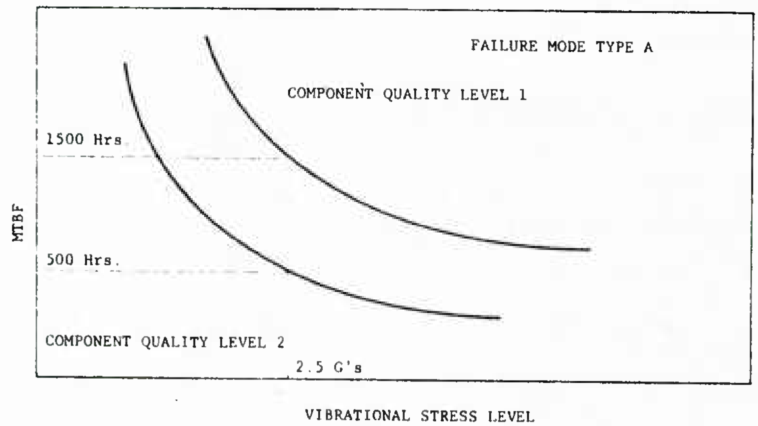


Figure B-2 SAMPLE MTBF VS. STRESS RELATIONSHIP

The prime objective of the center is improvement of helicopter system and component effectiveness through application of the reliability prediction, growth and control model described in this report. Within the economic constraints of manpower and monetary resources, significant accumulated reliability data and knowledge must be effectively utilized to achieve this objective. Thus, the "user community" is that body of individuals and organizations responsible for upgrading and maintaining component and systems reliability. Included among the users would be:

[4]Reliability And Maintainability Planning Guide For Army Aviations Systems And Components, U.S. Army Aviation Systems Command, AVSCOM Pamphlet No. 72, July, 1974.

DEPARTMENT OF DEFENSE

Policy Planning
Coordination with Other Agencies

ARMY TECHNICAL DIRECTORATE

Program Planning
Technical Direction

THE ARMY AVIATION RELIABILITY ANALYSIS CENTER

Policy Planning on Reliability
Directives for Implementation
Specification Review
Etc.

ARMY PRODUCT AND PROGRAM OFFICES

Project Initiation
Project Direction and Control
Reliability Control

ARMY SPECIFICATION WRITERS

Standards
General Specifications
Equipment and Components Specifications

ARMY LOGISTIC PLANNERS

Parts Inventory Control
Maintenance and Service Facilities

CONTRACTOR MANAGEMENT

Contracts Manager
Project Manager
Reliability and Quality Control Manager

HARDWARE DESIGN AND MANUFACTURE

Design Engineers
Reliability Engineers
Specification Engineers
Quality Control Engineers

COMPONENT PART MANUFACTURE

Design Engineers

Materials and Process Engineers
Reliability Engineers
Quality Control Engineers

Thus, a very large and diverse group of users is envisioned. While it is true that they all have one common interest, the functions performed and decisions rendered certainly are different. The center must provide all with certain data and information to enhance the carrying out of their individual functions. Yet, it would be completely impractical to attempt to satisfy all individuals with common information.

One solution is to define each potential user of reliability information in terms of his function, scope of responsibility, etc. From such an analysis, the individuals' information requirement could be determined. An attempt would then be made to fulfill the specific need of each by selective dissemination--tailoring the center output information to satisfy each specific use function. This would represent a completely unmanageable task of data processing and communication.

At the other extreme, fixed outputs can be postulated in sufficient number and variety to perfectly satisfy all potential users. Clearly, this would require formatted outputs of great variety, many of which would serve only a few users. The operational inefficiencies of such an approach are evident.

A third alternate is recommended. It represents a compromise between the two extremes -- certain use functions are enough alike to permit grouping. This permits an analysis of the information needs of a small number of groups and subsequent information dissemination accordingly. A suitable classification scheme has been developed around similar responsibility interest and is described in Section 5.0 of this appendix. In addition, the center is one of its own users. The idea of the center being one of its own users may be better understood if we use a simple analogy.

Consider a "black-box" device having an input and an output as well as an external feedback loop returning part of the output back into the device for modifying the original input intelligence. Input information is derived from suitable selected sources. The output is the information disseminated among the interested user community. The center now represents the black-box device. Its characteristics must be so designed that the input information is transformed into readily acceptable and communicative forms. A vital concern of the center would be analysis and decision making, formulating and recommending courses of actions, new evaluation techniques, better utilization of data resources, etc. The logical input information for such activities is data which has already been categorized, reduced and summarized -- which generally is the form of the raw data having been acted upon by routine functions.

Thus, the analysis function can be compared to the feedback loop of the analogous black-box system and can be classified as a user of the Center.

It should be apparent from this discussion that the user community represents a broad segment of the defense community whose reliability information needs are numerous and complex. Through logical classification of the community into segments of similar interests it is possible to formulate a manageable program to supply their particular reliability needs.

In an ideal sense, the hardware configuration of the center would be developed from the functional requirements as determined by the types of operations and the data volume called for by the objectives of the center. Utilizing input data estimates and their growth characteristics, the output requirements, and the implementation plan, a computer system could be selected in accordance with criteria of effectiveness. These criteria include:

1. Storage capacity and its expandability
2. Process times of computer and I/O devices
3. Expandability of overall system
4. Flexibility
5. Availability of programming aids (compilers, library of tested programs, etc.)
6. Costs
    a. Capital investment (rent purchase or share)
    b. Programming
        (1) Systems and Standards

(2) Initial system

(3) Continuing implementation

c. Operating

For the initial data analysis operation and perhaps a longer period of development, however, the center should operate with a minimum of computer support. One of the main foundations of the fully operating center will be the programming (software) system by means of which the data is processed and reliability analysis performed. Figure B-3 shows a typical programming system. This must be developed in detail during the implementation phase to assure efficient computer use.

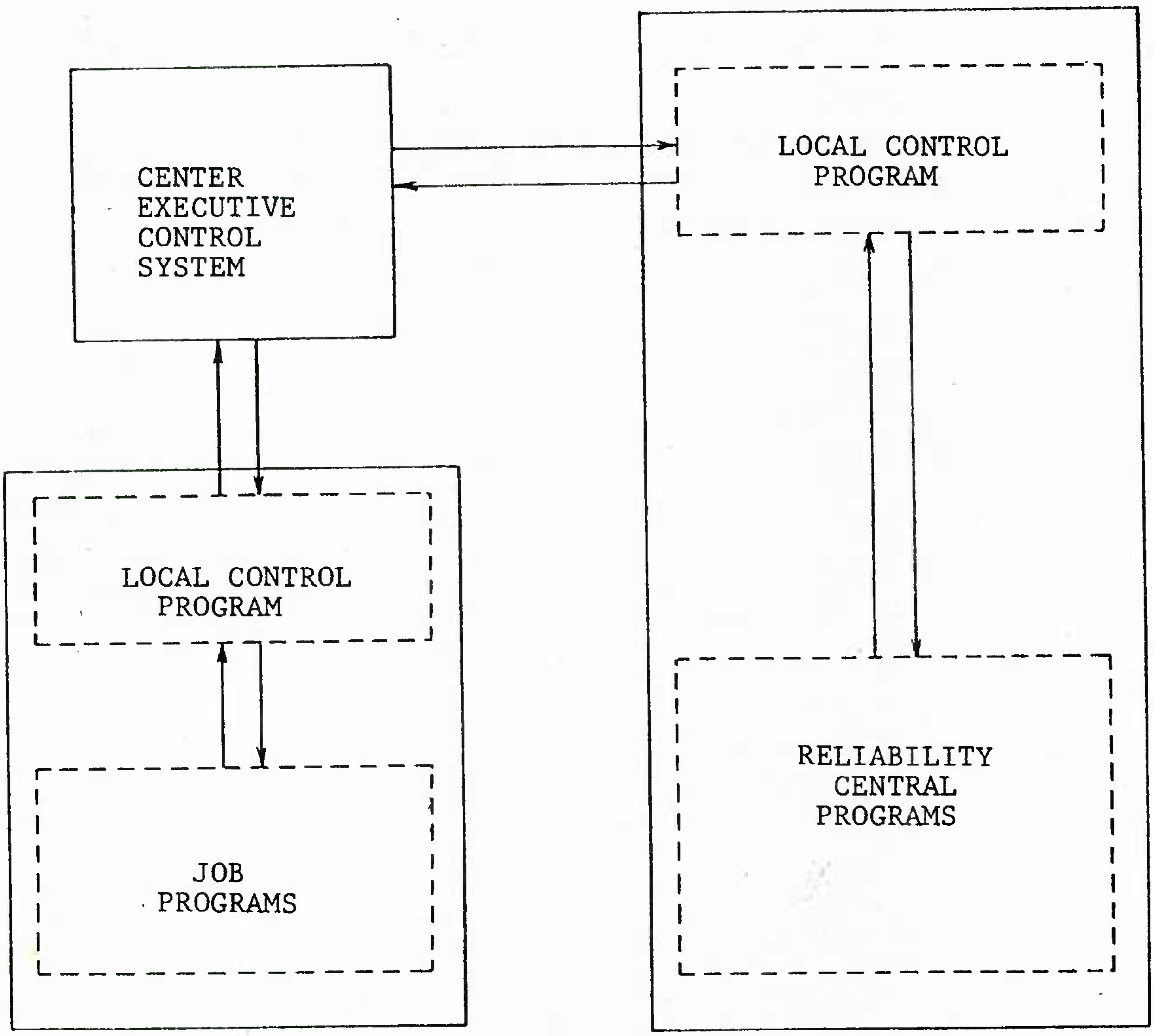


Figure B-3 TYPICAL PROGRAMMING SYSTEM

4.0 ORGANIZATIONAL REQUIREMENTS

In this section the plan for the center with regard to scheduling, organizing and staffing is discussed. In addition hardware requirements are also briefly discussed.

Figure B-4 presents a conceptual picture of organizational milestones. It attempts to characterize the concepts involved and identify implementation milestones. It is envisioned that the organizational plans would involve some of the events, general concepts and considerations within the approximate time frame shown in Figure B-4.

The major efforts depicted in Figure B-4 are the following:

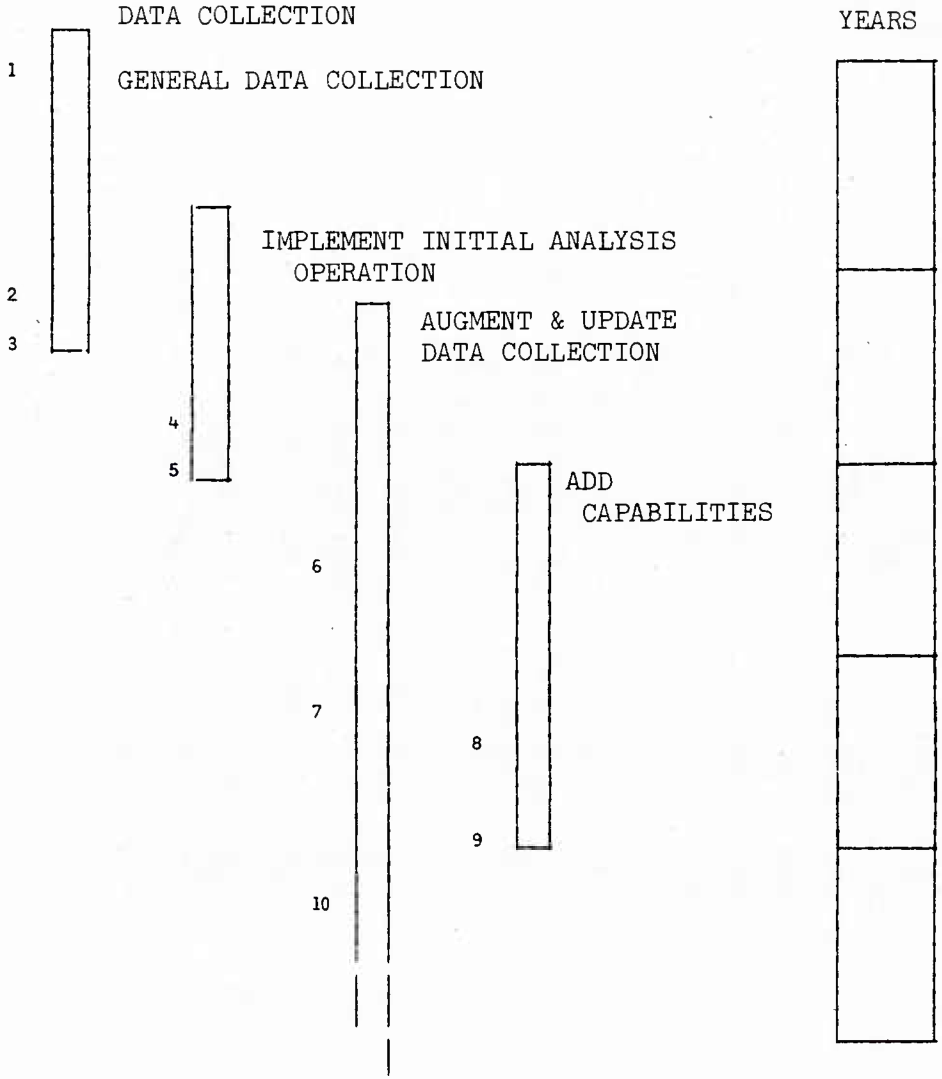
a. Data Collection Effort

During this effort initial data collection would be performed. Data would be collected on helicopter drive components exclusive of engines. The output of this effort would consist of three (3) items:

(1) The data itself in the center's format. Figure B-5 provides a representative example of an output data summary form. Figure B-5 depicts the manner in which trends and relationships between the reliability factors could be minimized. Many variations of the output summary format can be designed based on effectiveness considerations. This is a preliminary form which must be developed to meet the full needs of the reliability efforts.

(2) The analysis programs required for record-by-record analysis of this data.

(3) A notebook containing analyses of the data in tabular and plotted form for ready reference by user groups.



1 IMPLEMENTATION PLAN AVAILABLE
1a GENERAL STORAGE & RET. SYSTEM DESIGN
1b DETAIL STORAGE & RET. DESIGN
1c MACH. DATA
1d HANDBOOK ON DATA

2 MACHINABLE DATA AVAILABLE
3 HANDBOOK ON HELICOPTER DRIVE COMPONENTS

4 INITIAL MODEL ANALYSES & OUTPUTS (See Figure B-5)

5 OPERATE ON DRIVE SYSTEM PARTS BEARINGS, GEARS, ETC.

6 OPERATE ON ENGINE PARTS AND AIRFRAME PARTS

7 ALL HELICOPTER PARTS, MATERIALS, PROCESSES & INSPECTIONS

8 ADD OUTPUTS, HANDBOOK COVERING ALL COMPONENTS

9 ADD QUERY LANGUAGE & CONSOLE

10 R HANDBOOK (INDUSTRY COORDINATION RELEASE)

Figure B-4 CONCEPTUAL MILESTONE CHART AND MASTER SCHEDULE

	DOCUMENT TITLE	MFG.
DATA DATE:		
ENTRY DATE:	AUTHOR & AFFILIATION	PT. NUMBER

BASIC TECHNOLOGY

AIRCRAFT DESIGNATION	AIRCRAFT SUBSYSTEM	PARTS TYPE	FABRICATION
AH-1G	ENGINE	BEARING	CASTING
TH-1G	TRANSMISSION	G BARS	MOLDED
UH-1A	DRIVE TRAIN	SPLINES & CLUTCHES	STAMPED
UH-1B	ROTOR HEAD	HOUSING	
UH-1C	ROTOR CONTROL	SEALS	
UH-1D	ROTOR BLADE	SPACERS	MACHINING
UH-1H	AIRFRAME	BEARING LINERS	MILLING
UH-1M	FLIGHT CONTROLS	RETENTION HARDWARE	DRILLING
OH-6A		CASES	GRINDING
OH-13K	AIRCRAFT COMPONENTS	SHAFTS	DEBURRING
OH-13S	COMPRESSOR	NUTS	
TH-13T	COMBUSTION	BOLTS	
OH-23B	TURBINE	MATERIAL	
OH-23L	CASES	STEEL	
OH-23D	LUBRICATION	ALUMINUM	
OH-23G	FUEL	COMPOSITE	
CH-34C	AIR	TITANIUM	
VH-34L	TORQUEMETERS		
CH-47A	ELECTRICAL		
CH-47B	EXHAUST		
CH-47C	POWER TRAIN		
CH-54A	OTHER		
CH-54B			
TH-55A			
AH-56A			
OH-58A			

PREVIOUS TESTING	STRESS LEVEL	CODED STRESS LEVEL

NO. TESTED	TEST DURATION	TOTAL HRS./CYCLES	NO. FAILED

	FAILURE MODE/MECH.	TTF/NCF

Figure B-5 - DATA REDUCTION SUMMARY FORM (SAMPLE)

The programs, which are one of the outputs of the data collection efforts, are embedable in the program system planned for the initial data analysis operation. They are thus useful both for the immediate notebook preparation and are required as elements of the eventual programming system.

b. Implementation of the Initial Analysis Operation

An initial operation is planned which will demonstrate fully the viability, utility and purposefulness of the planned system. The intent is to prove validity of the assumptions underlying the effort through actual services to the user community. The outputs defined at this time will be fully operational, but exercised only on the data from the data collection effort above. The initial operation is an evolutionary step towards full operation, as becomes apparent by inspection of the master schedule, Figure B-4.

c. Update Data Collections

Effort under (a) above is conceived to generate a static body of data suitable for the purpose of the initial analysis operation. To achieve full operation, data must be collected continuously on all parts and processes within the data bank, and new parts must be added as required. Updating and augmenting of the data collections is therefore a continuing task, as indicated on the schedule.

d. Additional Capabilities

The capabilities for the initial operation require augmentation for full operation. The major elements are addition of services, through specific outputs and through improved query capability. A query language will permit flexible use of the data bank and analysis capability by reliability professionals with only minimum training in computer technology.

While this increase in capability is defined by a milestone (as shown in Figure B-4), it should be realized that additional requirements would be defined and justified in use. Examples include analysis of hardware failure rates and the computation of the effect of component data change on such hardware failure rates. These capabilities lead to the initial reliability prediction handbook for helicopter components.

One of the major problems of appropriately structuring the center's organization is to assure integration between the separate task types which make up the Center's mission. This subject requires close consideration not only of the individual tasks but of the way in which clerical and professional people can be motivated to cooperate actively. Figure B-6 presents a possible organizational structure.

Each organizational subgroup must have a mixture of professionals such that both task-oriented and subject-field-oriented personnel cooperate within each subgroup. One example would be an analysis group charged with bearing reliability modeling and prediction. A statistician should be available within the analysis group to work with bearing specialists in the solution of problems, the generation of trend information and the like. Similarly, the organizational component charged with computer programming should have reliability-oriented staff members as part of the group.

On the surface, it would appear that separation by disciplines such as mathematicians, computer-oriented staff and component-reliability experts would optimize effectiveness, by promoting full utilization of individuals, flexibility of scheduling work and assembly of task groups. In practice, a project-type organization is more desirable because each group can be charged with the accomplishment of specific tasks.

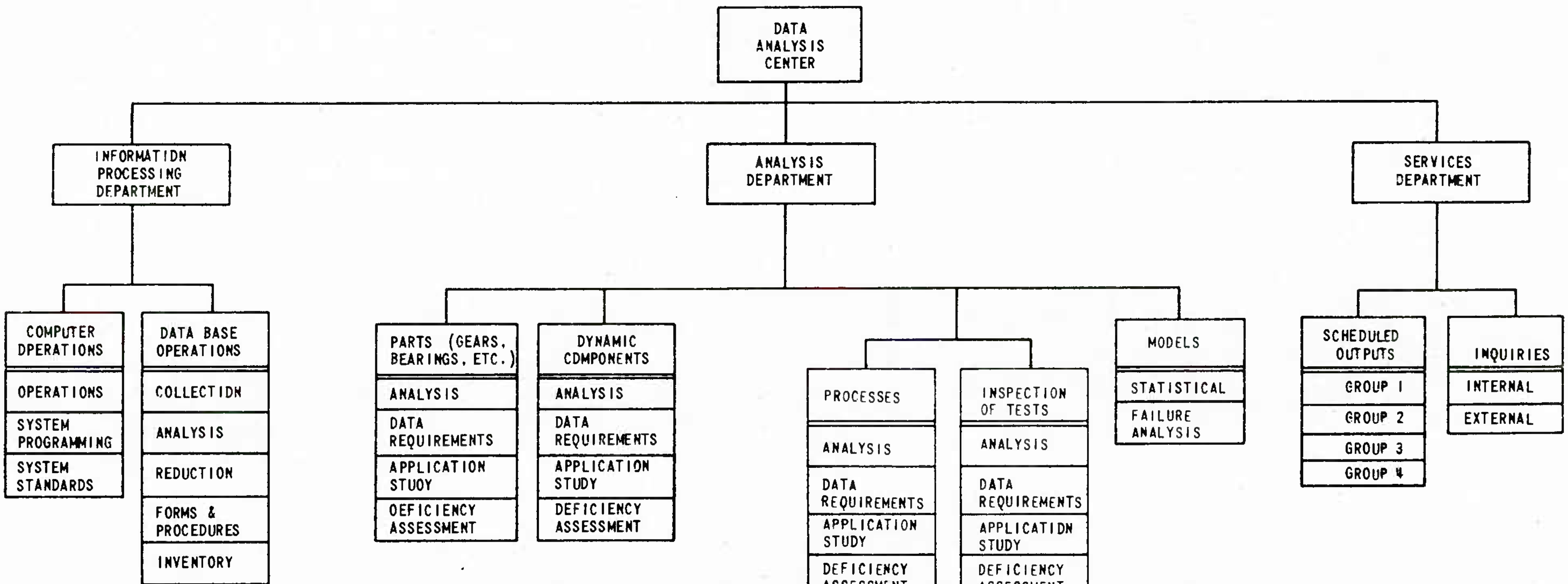


Figure B-6 ORGANIZATIONAL STRUCTURE

Thus, Information Processing, Analysis and User Service can be organized as separate groups with well-separated responsibilities. Within each group, the tasks may be subdivided and corresponding organizational entities defined. The staffing of these groups can be designed so that each may be self-supporting to the maximum extent. In this way, responsibility for performance is clearly assigned.

Tasks which require broad support of many functional groups can be separated, and can be the responsibility of individuals who will act hoizontally across the organizational structure. Analysts, who reside in an identifiable sub-organization with a specifically assigned function, are an example.

Purely service functions, such as drafting and reproduction may also be separated and identified.

A hypothetical staffing schedule based on the master schedule is shown in Figure B-7. It presents the build-up of professional and non-professional staff as the Center evolves toward initial operation and full operation. This schedule is conceptual in that it shows relative rate of staff growth. Specific numbers of personnel can only be determined through detailed analysis of data volume and use. Figure B-7 indicates that the most rapid growth occurs in transforming the initial operation into the full service Center.

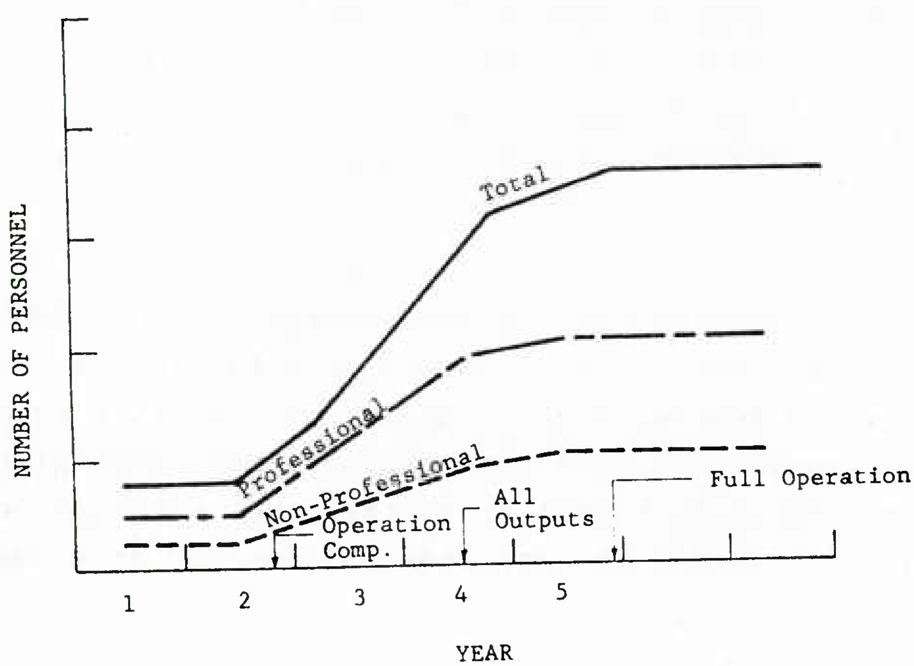


Figure B-7 STAFFING SCHEDULE (Hypothetical)

The duties and assignments of the staff are discussed below.

It is envisioned that the Center would need personnel functioning as follows:

> A Technical Director in charge of all aspects of the reliability data center. He should be assisted by a Senior Technical Advisor and Department Chiefs.
>
> A Director in charge of administrative aspects, including personnel administration, property and document control, reproduction and drafting. He also would assist the Technical Director in the preparation of plans and schedules, and in measuring the timeliness and efficiency of other organizational components.
>
> A Chief of the information processing department in charge of computer operations, maintenance of the data base and planning/execution of additional services.

As the Data Center grows into a fully operational Data Center, the organizational structure as shown in Figure B-6 would require personnel having the following titles:

1. Technical Manager
2. Technical Advisor
3. Administrative Assistant
4. Data Base Manager
5. Chief Analyst
6. Service Manager

The organizational structure, staffing requirements and scheduling considerations discussed here for initial and full operation represent only two of many possible organizations. A major effort during the implementation planning phase would be to specifically address the organization and staffing requirements at each stage of the Center's development.

The processing requirements of the Center are determined in part by the operating environments, and in part by the output requirements described in Section 5.0. Inasmuch as the functional outputs will increase as the Center proceeds from initial operation to full implementation and the data base will grow as it encompasses more input sources and more components, the data processing system must be expandable while retaining flexibility. Flexibility is required to meet damands arising from new orientations in reliability analysis and management as well as from more complex analytical procedures and more sophisticated programming techniques.

Recognition that reliability facts about parts, materials, and processes information concerning documents would be processed, motivates the design of the Center. Standard data formats in an easily expressible entry language would be required to accommodate the many expected inputs from a large number of sources. Flexibility would be maintained by permitting the user to define the vocabulary and structure of a new data element or set of elements to the system.

The data would be structured logically in the form of a rooted tree independent of its physical location. Branches would emanate from the root with diverging branches emanating from the next lower level of nodes. Each node would correspond to named data items and the subtree emanating from that node would represent the structure of the item. The logical address of a data item would define the relative position of the item within the tree and would be coded so that a unique code is created for each item in the data base.

Reliability data would be retrieved through directory search. The directories would translate the names of items into logical codes and then determine the physical location where the item with a designated code would be stored. Retrieval would be accomplished through the Reliability Central Local Control Program communicating with the pooled data storage via an Executive Control System.

File management and data analysis is envisioned being accomplished by the Job Run Request routine which would specify the processing task to be performed. This routine would call for a linking of subroutines designated by a Job Entry Request routine and containing independent programs defined by a Program Entry Request Routine.

To facilitate the processing of large quantities of data it is convenient to consider three levels of data: raw, reduced, and summary. The raw data consist of detailed test results such as are exhibited in the entries of a matrix test. The reduced data may be a scatter diagram, a curve, or an equation. Summary data may specify a failure rate, acceptable reliability level, or denote qualified/unqualified.

It is absolutely essential that an audit trail connect each datum in the data file to the originating documents. These documents must be logged in accession order, with accession numbers. Thus, in case of question, need for greater detail or desire to inspect non-machinable auxiliary data, a document from which the computerized file element was produced may always be obtained.

Where the original document is either classified, or contains industrial proprietary data with restricted distribution rights, this information also must be carried into the file by means of separate information bits.

Any analysis, summarization or print-out which utilized classified and/or proprietary data will become "contaminated" and will carry an appropriate symbol of its classification. It is the responsibility of the analyst to determine whether a summarized print-out partly based upon classified data is or is not classified. Obviously, this depends on the nature of the analysis in merging of classified and unclassified data and on the method of presentation.

Proprietary data, similarly, will contaminate all output for which it is sued. In this case the analyst must determine whether the proprietary nature of the original data has been eliminated through deletion of corporate identification, merger of data across individual but separate restricted data sources or the like.

It would be the responsibility of the Center to use the data trail facilities built into the system to avoid release of classified and/or proprietary data to unauthorized recipients.

5.0 FUNCTIONAL OUTPUTS

The initial analysis operation provides critical outputs that are to be implemented in such a manner that they serve as a springboard for the full operation of the Center. During full operation, the outputs can be expanded and additional outputs added to obtain optimum operation.

Although the outputs can be defined separately, they are by no means independent. They not only can share specific subroutines, but some outputs require summary information which can be provided by other outputs. A good example of this is the preparation of part application data summaries. Flexibility can be provided in the initial outputs by the query procedure. The query procedure would enable one to specify parameters which control the output options and data items to be processed.

Figure B-8 shows a possible classification of parts indicating their hierarchy and class delineation. This figure is useful for keeping in mind the several levels at which data are available for entry into file. The audit part identification system, which would be used, must attempt to provide a measure of consistency with other reliability data services. This topic must be described in detail prior to implementing the Center.

To provide efficient storage and exchange of data the data base can consist of three data banks for raw, reduced, and summary data (see Figure B-9). The raw data bank can be stored on magnetic tapes with a minimum of access required. Figure B-10 depicts a typical structure of the raw data bank. The reduced data bank can be stored on magnetic disks and would accomodate heavy access. The summary data bank can contain the results of the various outputs.

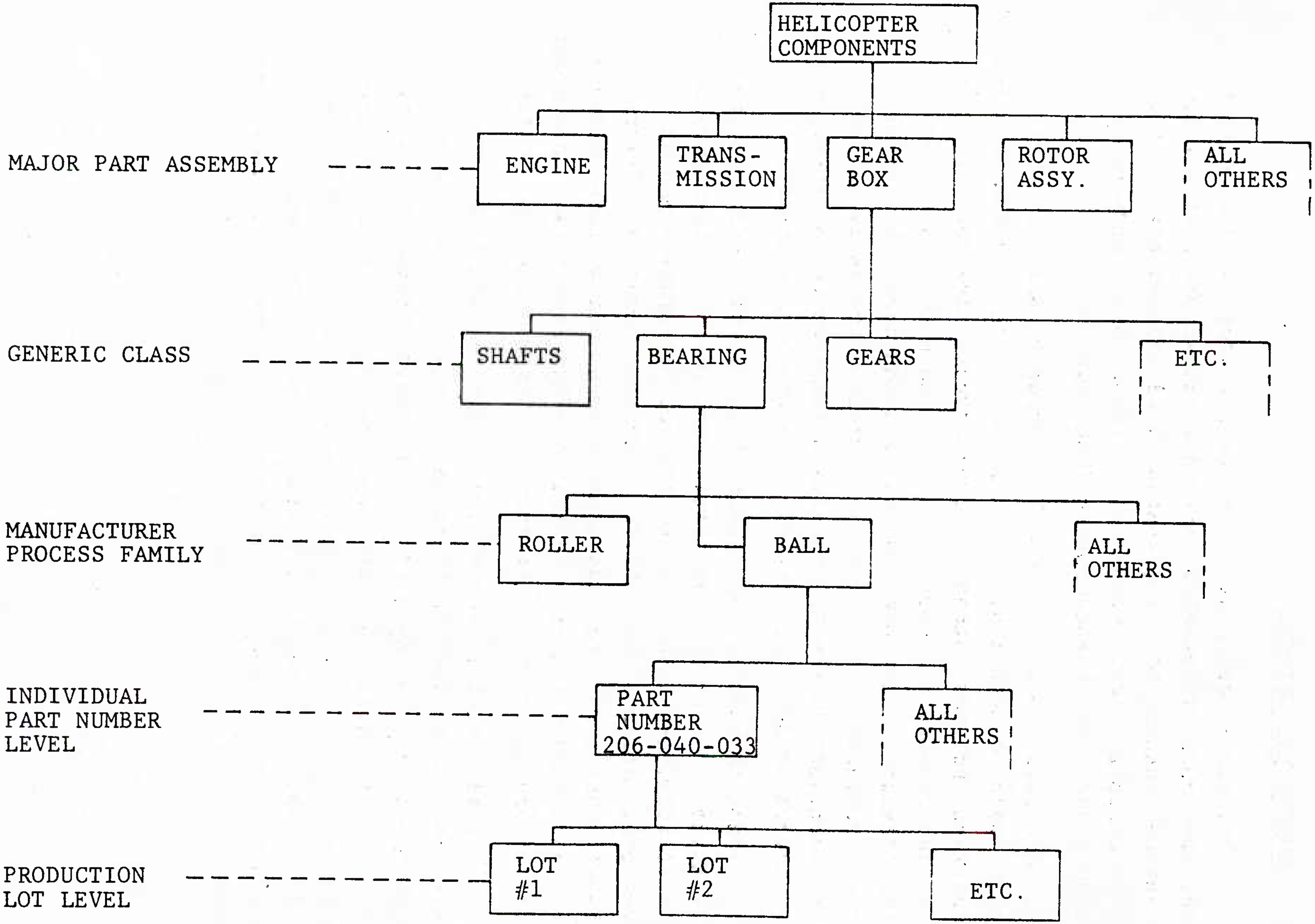


Figure B-8 HIERARCHY OF PART AND CLASS DELINEATION

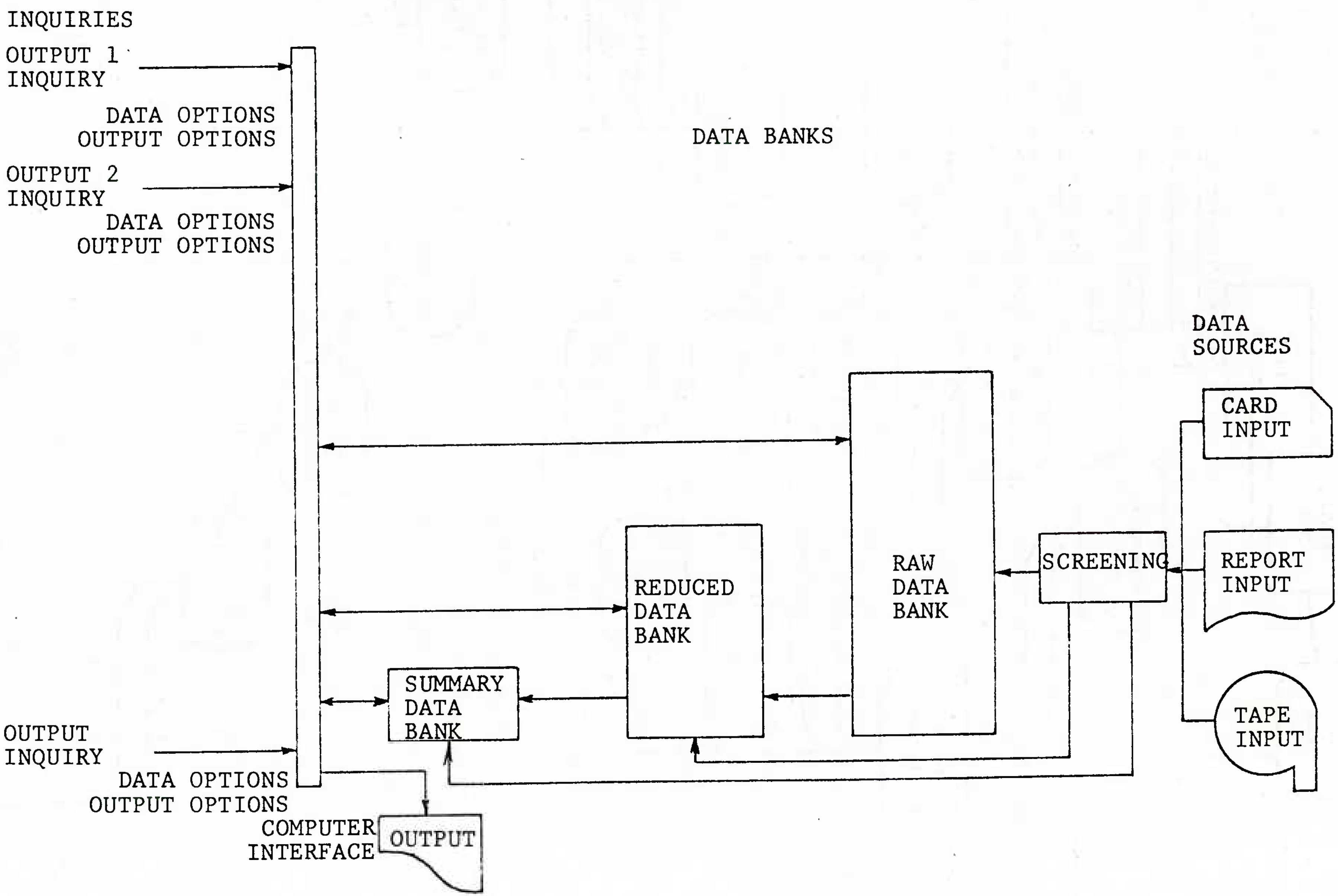


Figure B-9 DATA FLOW (FULL OPERATION)

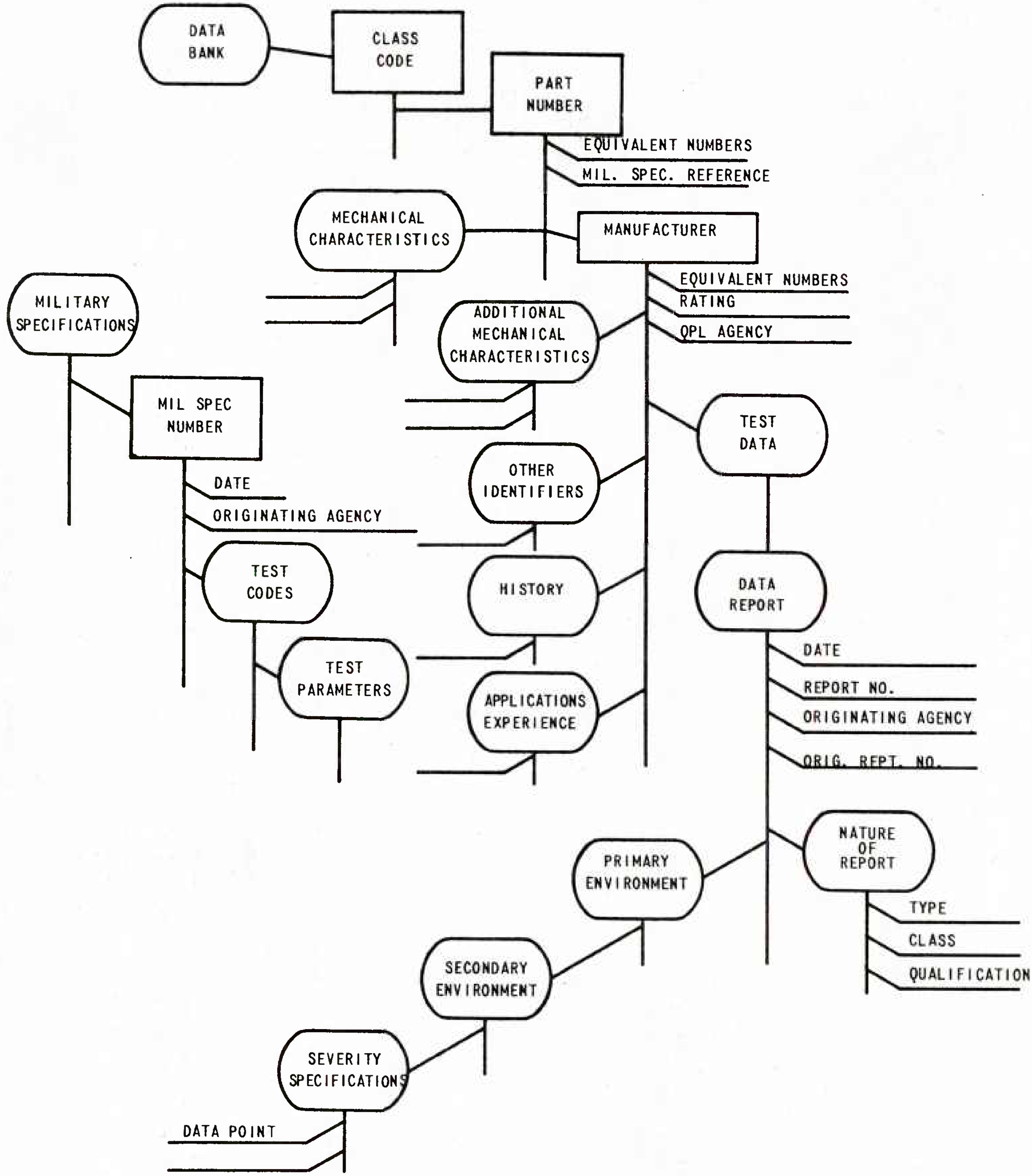


FIG. B-10 TYPICAL STRUCTURE OF RAW DATA BANK

The outputs could be implemented through a combination of manual and computer effort. The output flow charts to be developed for the final plan would indicate the division of this effort. As the analysis procedures are more clearly defined and experience with the data base is attained, more tasks can be turned over to the computer system. However, the center must always remain more manually oriented than most computer systems by nature of the diversification of the data base. An audit trial for all outputs should be provided. This enables the analyst to interpret the computer results and perform manual analysis which the computer is incapable of performing.

The data analysis procedure specified should make extensive use of statistical models and tests. The prime objective of each output would be the consolidation of large masses of test data into, hopefully, a homogeneous grouping for analysis and fomulation of conclusions. Statistical methods provide the techniques by which these processes may be accomplished. They further permit statements of uncertainty of conclusions drawn.

Those statistical techniques that have proved successful in reliability analysis must be applied to the analysis effort. The most efficient methods must be selected to provide a valid quantitative statement of the observed behavior. Merging of data from a large numer of individual tests (experiments) complicates the problem. Each testing agency has its own peculiar set of variables, or uncontrolled parameters in addition to the specified conditions. In combination with data from other testing agencies, the dispersion can become quite broad and must be compensated for during analysis.

Parametric techniques will be chosen wherever practicable in preference to distribution-free methods. The former have been more fully developed resulting in availability of practical techniques for most reliability analysis situations. Also, they have an inherent advantage in efficiency of parameter estimators and hypothesis tests. Certain distribution-free methods may become necessary if it is later found that portions of the collected data do not meet the qualifying assumptions for parametric modeling.

A listing of the statistical routines, distributions and tests to be specified for the various operation analyses must be developed during the implementation phase. This includes definition, description and application to particular data steps.

In order to define the functions of the operation in detail, it is considered desirable to set up an output matrix (see Figure B-11). This matrix can be used as a guide to define criteria essential to implementation of the outputs. It also will prove valuable in pointing out gaps in definition and duplication of effort among the various outputs.

In its preliminary form, the matrix attempts to provide an overall view of the initial operation. It defines input parameters, output formats and data processing required for each of eleven initially considered outputs. Required items for each output are indicated by the word "YES", conversely "NO" is inserted in cells of parameters not used for the output. Required items must be defined further during implementation. Major items to be defined are:

1. output data formats, tabular and/or graphical,
2. itemized listing of input items required and,
3. functional flow charts depicting process steps required to devise formatted outputs from input data.

TITLE	OUTPUT PRESENTATION				DATA BANKS				ANALYSIS		
	SOURCE DOCUMENT	COMPUTER TABULATION	COMPUTER PLOT	MANUAL SUMMARY	SOURCE DOCUMENT	RAW	REDUCED	SUMMARY	STATISTICAL ROUTINES	MANUAL	FLOW CHART
1. Publication of Part Failure Rates.	NO	YES	YES	NO	NO	NO	YES	NO	YES	NO	YES
2. Failure Distribution Analysis.	NO	YES	YES	NO	NO	NO	YES	NO	YES	YES	YES
3. Part Parameter Characteristics Versus Stress and Time.	NO	YES	YES	NO	NO	YES	YES	NO	YES	NO	YES
4. Preparation of Failure Mode Summaries.	NO	YES	NO	NO	NO	NO	YES	NO	NO	NO	YES
5. Publication of Documented Reliability Parts List.	NO	YES	NO	NO	NO	NO	YES	NO	YES	NO	YES
6. Publication of Validated Reliability Data Parts List.	NO	YES	NO	NO	NO	NO	YES	NO	NO	YES	YES
7. Preparation of Part Application Data Summaries.	NO	YES	NO	YES	YES	NO	NO	YES	NO	YES	YES
8. MFG's Qualification, Production Data.	NO	YES	YES	NO	NO	YES	NO	NO	YES	YES	YES
9. Reliability Improvement Rates.	NO	YES	NO	YES	NO	NO	YES	NO	YES	NO	YES
10. Test Programs Planned and Underway.	NO	YES	NO	NO	NO	NO	YES	NO	NO	NO	YES
11. Specification Reviews	NO	NO	NO	YES	YES	YES	YES	YES	YES	YES	NO

FIGURE B-11 - FUNCTIONAL OUTPUTS (INITIAL OPERATION)

Supplemental material such as nomenclature definition and analysis criteria must be included where appropriate.

The totality of items listed in the matrix and reference is by no means sufficiently detailed to produce computer program and manual analysis instruction. However, it does provide the principles and basic design documentation for developing, detailed flow charts, and operating procedures.

Each of the outputs depicted in Figure B-11 are described below.

Output No. 1: Computation and Publication of Part Failure Rates

Merged failure rates based on statistical assumptions would be computed and published for all parts at the test and/or operational stress conditions for which data is in the data banks. In addition, regression coefficients would be computed for median failure rate versus stress wherever available data permits. Operational procedure will permit failure rate computations for item descriptors other than part number.

Output No. 2: Failure Distribution Analysis

Laboratory life test data on component parts would be analyzed to determine failure distribution. Included would be correlation with Weibull and other parametric distributions known to be applicable for particular classes of components. Such information is useful in designing and devising more efficient inspection sampling plans. It could also be extremely useful in reliability analysis to define curves (i.e. determine whether hazard rates decrease, remain constant, or increase with time).

Output No. 3: Part Parameter Wear Characteristics Versus Stress and Time

Provide various graphical summaries of wear characteristics from accumulated life and environmental test data. Several graphical computer formats could be considered to fully characterize wear behavior. Included would be long term consideration employing sophisticated analysis such as:

1. Multiple linear regression
2. Non-linear curve fitting
3. Transformation of stress scales to permit curve fitting.

Output No. 4: Part Failure Mode Summary

Failure mode analyses that summarize part failure modes according to the applied stress conditions under which they were observed would be provided. Failure mode is defined as the physical description of the manner in which a failure occurs and the stress responsible for the occurance.

Output No. 5: Preparation of Documented Reliability Parts List

A Documented Reliability Part is defined as a part for which a sufficient volume of properly documented reliability test data has been accumulated such that failure rates have been determined to a reasonable level of confidence. A periodically issued list of parts that qualify to pre-established criteria can be supplied. This listing would be useful for selecting parts with known demonstrated reliability levels, both in laboratory tests and field operation.

Output No. 6: Determination of Valid Data Parts Lists

This would be a comprehensive listing of those parts for which properly validated test data are in file.

Output No. 7: Preparation of Part Application Data Summaries

Application data summaries would be provided for parts in files, containing such information as:

1. major mechanical characteristics with tolerance limits
2. maximum use ratings
3. specified environmental capability
4. performance versus stress functional relationship including derating curves
5. application considerations as derived from past operating experience

This information would provide the user with factual data on the capabilities and limitations of parts to foster well-engineered equipment designs.

Output No. 8: Analysis of Manufacturer's Qualification and Production Test Data

This analysis would provide process defect and inspection efficiency information as well as provide a continual check on quality. Data generated during quality inspections and tests would provide a steady reliability and environmental data volume build-up which will enhance the precision of production reliability analyses.

Output No. 9: Reliability Improvement Rate Report

Reliability improvement rate data that reports failure rate versus date of manufacture would be provided. As a scheduled output, the Center could issue annual summaries showing failure rates, by year, for each component category and generic part class. The information may be obtained for other part groupings and different time increments at the option of the requester. The failure rate improvement data would permit a measure of overall reliability growth as well as, for example, determining whether certain part groupings are reaching design maturity.

Output No. 10: Preparation of Summaries of Test Programs - Planned and Underway

The Center through its normal relationships with other reliability activities could maintain cognizance over test programs in planning and in progress. Technical information regarding the nature and design of these test programs can be coded into the information storage files. Periodic summaries can then be distributed among users. Such summaries would improve planning of test programs and minimize effort duplication.

Output No. 11: Specification Review for Cancellation, Consolidation, and Updating

Specification review would be a routine function of the Center's specialists for the purpose of maintaining military specifications at a high level of currency and usefulness for procurement of parts material. During the initial operation phase, the activity can be limited to helicopter drive train parts. With full operation component part specifications, and eventually equipment and system specifications can be covered.

Broadening of the data banks to include large quantities of data on those parts included in the initial operation, and expanding into other component parts will give incentive and justification for developing more sophisticated analysis techniques. This naturally can lead to utilization of added capability in providing additional output intelligence. A brief description of other outputs for consideration during full operation are presented in the following paragraphs.

(1) Inventory of Data Files

Provide inventory printouts that tabulate all parts on file. This printout would include part number order within each recognized generic class.

(2) Part Failure Mechanisms vs. Stress and Time

This would be an extension of Output 4, Failure Mode Summaries; it would extend description of part failures from the more cursory level to fundamental processes taking place within materials or at material interfaces. The transition would depend entirely on the availability of failure mechanism definition on a sufficiently broad variety of part types and stress conditions.

(3) Determination of Preferred Parts and Material Lists

Once data on a sufficient number of part and material classes and part types are incorporated into the files, preferred parts lists can be determined and issued. This task would be a development of suitable criteria to separate out truly preferred parts from those offered.

(4) Part Failure Rate in System Operation vs. Laboratory Tests

This analysis would consist of comparing future rates obtained in system test with those obtained under laboratory conditions for the purpose of establishing use stress factors for the various field operating environments. All required data items can be included in structuring of the files. Search by stress class descriptors and data merge capability would also be incorporated. The current limitation is in accumulation of a sufficiently broad data base to permit useful comparisons.

(5) Identification of Relationships Between Reliability and Design, Process and Application Variables

This function would be concerned with determining the areas where extra applied effort can yield significant reliability improvement as well as isolating those materials, design decisions, process techniques and inspection and tests that contribute to unreliability. The basis for this analysis would be designed into the file structure which permits efficient access to files via a wide range of descriptors.

(6) Guidance to Exploratory Development in Reliability Technology

This can be a service function of the Center. During daily operations, specialists can become cognizant of advances in reliability theory and and test and analysis techniques. Especially useful techniques, those requiring further development and gaps in technology would become evident. This knowledge should be utilized in preparation of project suggestions and contract work statements and monitoring of contracted studies in the area of reliability.

(7) System Reliability Prediction

In addition to capability for providing after-the-fact feedback on system reliability, plans would develop computerized reliability prediction capability. The techniques developed would make full use of the data banks and permit prediction at various stages of system design, development and production based on the procedure presented in Section 3.2 of this report and updated during the initial operation phase. This capability would prove mutually beneficial to the Army and its contractors through continual monitoring of reliability progress and growth during product development and production.

(8) Determination of System Reliability Needs

This function could be developed to assist in the preparation of specifications by supplying quantitative data on reliability levels required to accomplish the intended mission. This knowledge would be obtained by analyzing previous similar mission performance for deficiencies, problem areas, failure modes, etc. The various machine data files would be "massaged" for appropriate historical information but manual analysis could also be expected to play a major role.

6.0 INPUT REQUIREMENTS

Meaningful outputs of the data base would be contingent upon the characteristics of the input data which can be tapped for analysis. Briefly, the input data can be characterized on being made up of data from a changing technology, data that is unpublished and data from voluntary sources. Furthermore, previous data gathering efforts have indicated sizable volumes in various states of completeness, form and accuracy to exist among the many potential data sources. An essential task would be to ferret out pertinent and credible data from among the available bulk, identify it properly and put it into a readily usable form.

This section discusses the input data requirements, expected sources, preliminary internal scrutiny and reduction, and input data volumes.

During the initial operation and for some period beyond, the Center would concern itself primarily with data on helicopter dynamic components, either tested as discrete items or as a system element of a developmental or operating equipment. The discussion of input data is thereby justifiably oriented heavily toward parts data.

Two fundamental requirements of input data are quantity and quality. Inadequate quantities necessarily restrict the interferences that may be drawn from test results and seriously limit the precision of any inferences that are drawn. However, the availability of large data volumes by itself offers no positive guarantee that useful outputs can be derived. More important, the incoming data must be identifiable to the source item (e.g. tested and to the tests performed) and results must be credible. This characteristic of input data is defined as quality. Success of the system depends upon its availability to merge data from the multitude of sources into highly summarized, yet fully documented statements regarding part reliability and performance characteristics.

The reduction and merging process will be invalid unless the item tested is adequately identified and the tests conducted completely defined. Validation and qualification criteria can be devised to minimize the probability of incorrectly classified data reaching the data banks.

The extent to which generalizations are possible from test data would be contingent upon the variety of stress conditions or severity levels under which the part has been tested. In a well planned test program relationships between reliability parameters and stress can be developed. On the other hand, consider a part tested only at a single stress condition. Without risky a priori assumptions regarding acceleration factors it is virtually impossible to draw inferences regarding reliability at other than the one (or two) test conditions, regardless of the volume of data generated at these conditions.

It is believed that the desperate need of users that exercise direct influence over system reliability, namely design personnel, will be for factual data specifically oriented to a particular part, preferably at the particular application of immediate interest. This is in contrast to lumping together data from many parts to formulate generalized reliability information at the generic class level. Certainly the latter has many uses and the ability to merge data in this fasion is incorporated. The objective to provide data at the part level however demands that input data be identifiable at this level. Therefore, data accepted must be identified by part number.

Other requirements of input data must be determined during the implantation. However, the preliminary basic requirements of input information can be summarized as follows:

1. Quantity: Minimum data quantities will be essential to permit the various statistical analysis planned. There will be no absolute minimum limit, however, as outputs are sufficiently flexible to make effective use of any available data on parts of interest. Parts having little available data, of course, may not qualify for outputs using a minimum data quantity criteria.

2. Data Quality: Quality of data will be mose essential for generating useful outputs.

3. Broad Stress Coverage: To be able to supply output information applicable to a helicopter stress environment and severity level it is essential that data be available at numerous stress conditions well spread over the expected use range. Again, valid output can be derived for those environments for which data are on file but ability to extend conclusions to other stresses may be limited.

4. Data at Part Number Level: Input data on parts must be obtained at the part number level. In other words, the test must be identified to a particular part and not merely a generic class.

5. Primary Data Sources: Data accepted shall be that produced by the agency performing the test. Reports may be obtained through data exchange programs but the original document must be identifiable.

Collection efforts are to be directed toward searching out data that comply with these basic requirements.

Information Sources and Content

Input information to the center may be classified in two broad categories:

1. Raw test data and other intelligence directly utilized in deriving outputs.

2. The tools and rules by which the input data are trans formed into the useful output, including specifications, other criteria, analysis methods, computer programs, reliability technology, etc.

The former by far represents the largest bulk and, for purposes herein, is what is referred to when using the term "input data".

The principal raw input would be data collected from laboratory tests and field service of component parts and completed equipments. The facility would handle reliability data on individual components parts as well as complex systems. In addition to quantitative test data, qualitative information concerning modes of failures observed are usually reported in test reports and represent an important input. Further, a raw input encompasses many other forms of intelligence necessary for accurate reduction and interpretation of the reliability data. Most of these are alphanumberic descriptions. In this category is information such as:

1. Part design material and process specifications,
2. Part functional characteristics and ratings,
3. Application information on parts,
4. Purchase specifications pertinent to parts (Military or User),
5. Component/systems operational requirements including performance, environment, and reliability,
6. Failure analysis reports; definition of fundamental failure mechanisms such generated by physics of failure studies.
7. Design, material or process change reports,
8. Specification waiver requests and manufacturer recommendations, and
9. New materials technology.

Some of the information types of this latter group also represent inputs to formulate processing rules for raw data. Due to its dynamic nature the internal operation must continually formulate decisions for upgrading its analysis tools and criteria by utilizing intelligence derived from its own output.

The major data sources available would include:

A. PARTS TESTS

1. Vendors Qualification Test Reports
2. Vendors Production Test Reports
3. Vendors Development Test Reports
4. Vendors Reliability Test Reports
5. System,Component Contractor's Part Test Reports
6. System,Component Contractors Part Reliability Program Report
7. Government Agency Part Development and Improvement Test Report

B. SYSTEM TESTS

1. Development Test Reports
2. Production Test Reports
3. Reliability Demonstration Reports

C. FIELD REPORTS

1. Test Reports
2. Operation Reports
3. Maintenance Reports

D. GOVERNMENT AGENCY R&D INSTITUTION - INDEPENDENT LABORATORY REPORTS

1. Government Laboratory Reports
2. Physics of Failure and Related Studies
3. Fundamental Parts Information
4. Published Part Reliability Data
5. Parts Data Bank

The data presently being generated by the various sources would be presented in practically every conceivable format. During initial stages of operation, data would be occupied in the format chosen by the originating agency if it does not desire to severly restrict its input data flow. Therefore, part engineering evaluation of the data content of each report must be performed. The main objectives of evaluation is to establish that the data meets the qualification requirements and to extract or otherwise pinpoint the specific data items to be encoded for machine input. A specification manual specifying details of qualification, validation grade coding and exact data items must be developed to guide this evaluation.

Initially and for some years much of the input data would be in the form of hard copies of manually prepared reports. Other forms expected are punched cards and magnetic tape.

Input Data

Quality was discussed previously. A second characteristic of input data closely related to quality is validity. The following definitions are presented:

Qualification: Characteristics of item and test documentation that determine whether or not the data are accpetable input. Decision is yes-no; data are acceptable or not on the basis of supporting documentation.

Validation: The degree of reliance one might place in accepting the reported test results as a truly accurate representation of tested items behavior under the stated conditions. Validation codes can be assigned according to pre-established criteria to each report as received.

To quality for incorporation into the files incoming data must, as a minimum, contain the following documentation:

1. Identification by part number recognizable by the system. The primary identifier would be the Military specification part number (manufacturers' part number in the absence of Military part number); at the time a part is set up in the file structure suitable alternate identifiers (as indicated in file structure) and characteristics will also be established for cross reference. Subsequent data will be identified by any one of the alternate identifiers, but must contain at least one.
2. Part manufacturer and process family.
3. Manufacturing lot number and/or data of manufacture.
4. Data of part procurement.
5. Identification of any deviations in characteristics, inspection procedures, material processing, etc. from that established for the standard production part.
6. Statement of purpose of test (i.e., vendor specification, lot quality conformance inspection, etc.).

7. Date test started and test duration.

8. Test conditions completely defined including stress severity.

9. Part parameters monitored, measurement conditions and readout time points.

The primary purpose of the validation procedures is to provide a means for tracing and evaluating data generated under different degrees of outside monitoring. The intent is that data entering files are assigned a validation code simply signifying the nature of monitoring employed without attaching any significance to actual validity of data itself. The following validation grades have been tentatively chosen subject to review and approval.

- <u>Parts Data, Vendor-Generated</u>
  1. Witnessed and countersigned by cognizant Government Resident Inspector.
  2. Witnessed by non-Government representative of the procuring organization.
  3. Certified by responsible company officer.
  4. Not certified.
- <u>Parts Data User or Independent Test Agency</u>
  1 through 4 as above.
- <u>Parts Data from Equipment Tests</u>
  1 through 4 as above.
- <u>Field Data</u>
  1. Contractor performed service witnessed by Government Contracting Engineer.
  2. Contractor performed service monitored by Government designated system monitor.
  3. Contractor performed service certified by responsible company officer.
  4. Contractor performed service - no certification.
  5. Operational system maintenance actions utilizing reporting forms.
  6. Operational system maintenance actions reported by forms of lesser detail and verification.

The Validated Data Parts list will be derived by considering only data from certain specified "validation grades" which are considered at the present time to provide the highest assurance that stated results truly reflect part performance under the specified conditions. The validation method will be defined during the plan development.

Initial surveys conducted of prospective data sources have revealed that a sizable volume of data has been generated on helicopter component parts and can be made available as input. Sorting and screening can be expected to take a heavy toll, but the volume of useful input information now available for collection is substantial. Additional detailed surveys of data sources must be conducted with visits to the sources to determine accurate quantity, quality and validity. The volume estimates must represent the best judgement based on results of source surveys tempered by the considerations of quality and validity. During early stages files would be limited by the effort available to gather, evaluate and process data into the system as well as availability of computer programs for analysis and reduction.

In summary, substantial data volumes seem to be available from many sources in even more diverse forms and content. Judicious collection, screening and evaluation according to the basic criteria presented in this appendix would be absolutely essential to ensure that the Center is not overwhelmed by sheer volumes of data having little utility.